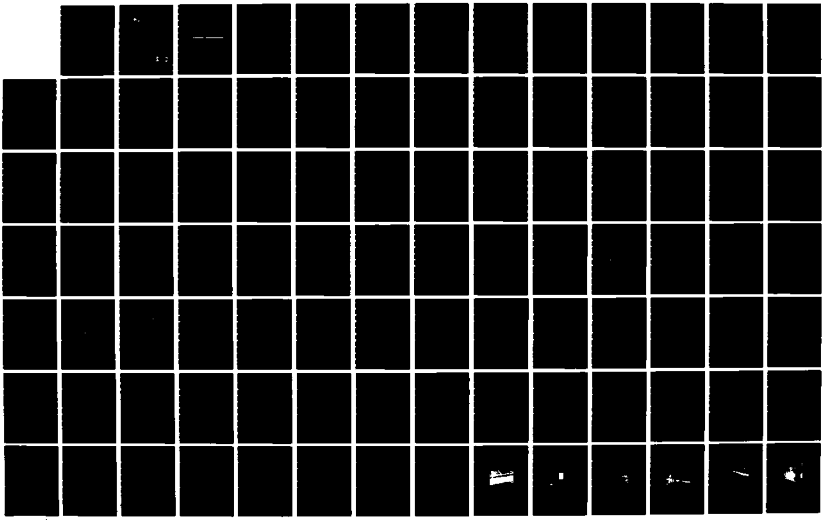
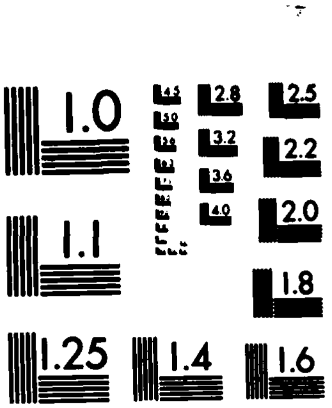
AD-A131 879 ACOUSTICAL BENEFITS RESULTING FROM INSULATION AND AIR LEAKAGE CONTROL IN..(U) MANVILLE SERVICE CORP DENVER CO RESEARCH AND DEVELOPMENT CENT.. J D VERSCHOOR ET AL. JUL 83 NCEL-CR-83.019 N62583-82-MT-033 1/2

UNCLASSIFIED F/G 5/5 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

CR 83.019

NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

Sponsored by
NAVAL FACILITIES ENGINEERING COMMAND

ACOUSTICAL BENEFITS RESULTING FROM INSULATION AND AIR LEAKAGE CONTROL IN FAMILY HOUSING UNITS

July 1983

An Investigation Conducted by
MANVILLE SERVICE CORP., R&D Center
P.O. Box 5108
Denver, Colorado

N62583-82-MT-033

METRIC CONVERSION FACTORS

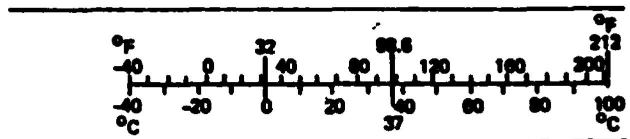
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CR 83.019	2. GOVT ACCESSION NO. AD-A131 879	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ACOUSTICAL BENEFITS RESULTING FROM INSULATION AND AIR LEAKAGE CONTROL IN FAMILY HOUSING UNITS		5. TYPE OF REPORT & PERIOD COVERED Final July 1981 - Sep 1982
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. D. Verschoor J. D. Haines		8. CONTRACT OR GRANT NUMBER(s) N62583-82-MT-033
9. PERFORMING ORGANIZATION NAME AND ADDRESS MANVILLE SERVICE CORP., R&D Center P. O. Box 5108 Denver, CO 80217		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 63-036
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Civil Engineering Laboratory Port Hueneme, CA 93043		12. REPORT DATE July 1983
		13. NUMBER OF PAGES 181
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Naval Facilities Engineering Command 200 Stovall Street Alexandria, VA 22332		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Family housing, energy conservation, retrofit sound transmission, air leakage, infiltration, insulation, walls, roof/ceiling

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In an investigation sponsored by the Navy Family Housing Office, a series of tests were conducted to determine the improvement in acoustical sound transmission loss resulting from housing envelope energy conservation retrofits involving increasing the insulation level and/or controlling the air leakage. The data generated will be utilized in selecting energy

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

conservation measures with maximum acoustical benefits, for retrofitting family housing units near aircraft operations, where excessive noise has been a problem.

Three wall and two roof/ceiling test structures were constructed to be representative of those in present Navy Family Housing Units. The sound transmission loss and air leakage rate (resulting from an induced pressure differential) were determined for each basic construction. Subsequently, various retrofit measures were performed, designed to improve sound transmission loss, thermal performance and/or air leakage control. Following the retrofit, the improvement in air leakage rate and sound transmission loss were again determined. The thermal conductance of the base constructions and that of the retrofits were calculated. For those constructions where present data was felt to be inadequate, guarded hot box tests were conducted to determine the thermal conductance of the construction.

Data are presented on the sound transmission loss, overall sound transmission class (STC), air leakage rate, and thermal conductance of the constructions tested. Typical (1982) retrofit costs are also estimated, so that benefit-to-cost performance can be analyzed.

SUMMARY

Under the sponsorship of the Family Housing Office of the U. S. Navy, an investigation was conducted of the reduction in sound transmission through exterior walls and ceilings resulting from energy conservation retrofit measures. It was known that improvement in sound isolation might be expected when the air leakage rate was reduced and the thermal insulation level increased. However, the magnitude of the improvement was not known for constructions typical for Navy family housing units. Improvement in sound isolation was desired because of the close proximity of many of the housing units to aircraft operations.

The investigation consisted of a literature search, to determine available information on the effectiveness of retrofit measures for reducing the impact of aircraft noise on residential units. This was followed by a field examination of housing units at a major base, in order to determine typical construction details. The laboratory portion of the investigation consisted of constructing full scale typical wall and roof/ceiling sections, and measuring the air leakage rate (ASTM-E283) and sound transmission (ASTM-E90) before and after various retrofit measures were taken. Thermal conductance before and after retrofits was calculated according to ASHRAE procedures. In four cases, where calculations were inadequate, guarded hot box thermal conductance determinations (ASTM-C236) were made.

Three wall and two roof/ceiling constructions were tested in the laboratory, as follows:

A - 2 x 4 frame wall on slab-on-grade foundation, plywood siding, gypsum board interior, fixed glazing.

B - 2 x 4 frame wall on crawl space foundation, stucco exterior, gypsum board interior, aluminum horizontal slider sash.

C - Concrete masonry unit (block) wall with stucco exterior, furred gypsum board interior, steel casement sash

D - 2 x 4 truss roof, 3/12 pitch, asphalt shingles on plywood sheathing, gypsum board ceiling.

E - Gravel on built-up roof, 1/12 pitch exposed, 2 x 6 decking, exposed beams.

It was confirmed that benefits in the form of increased sound isolation resulted from retrofit measures aimed at energy conservation (reduced air leakage and increased insulation level). The sound transmission of the wall structures was greater than the roof/ceilings tested. Therefore, efforts to improve the sound isolation of family housing units should start with the walls. Retrofit measures which attack secondary level noise leaks in the building envelope will not provide noticeable improvement in the interior noise level.

Windows were found to be a particularly weak link acoustically in the building envelope. Installation of storm windows was an effective improvement, especially when the storm glazing was thick (1/4 inch). Another effective retrofit measure was replacing the steel casement sash with an aluminum thermal-break double-glazed single hung window unit. This unit was designed for replacement purposes and provided a major improvement in the three areas of sound isolation, air leakage rate and thermal insulation. However, if windows must be opened for ventilation and/or cooling, no amount of sound isolation improvement to the wall or roof/ceiling would provide any overall reduction in the interior noise level in areas where the exterior noise level is high.

Acoustically treating a crawl space area provided improved sound isolation and reduced thermal conductance. Adding an insulated suspended ceiling provided a marked reduction in both sound transmission and thermal conductance. Acoustic treatment of an attic space roof vent did not improve the overall sound transmission properties of the roof/ceiling assembly.

Caulking and sealing of the exterior envelope reduced both sound transmission and air leakage. Sealing of exterior walls can be accomplished by caulking either the exterior or interior surface; the choice of exterior or interior surface depends on accessibility and cost. Only a slight improvement was found when both surfaces were completely sealed. Estimated installed cost for acrylic latex caulking was $1.10/linear foot, including labor, material and contractor markup. This makes sealing a questionable

retrofit on the basis of economic analysis when considering the energy conservation resulting from reduced air leakage. When installed by the owner at an estimated $0.06/linear foot material only cost, the retrofit is very benefit-to-cost attractive.

TABLE OF CONTENTS

Table of Contents (Continued)

LIST OF FIGURES

List of Figures (Continued)

List of Figures (Continued)

List of Figures (Continued)

List of Figures (Continued)

LIST OF TABLES

List of Tables (continued)

INTRODUCTION

The Department of Defense has had an active program to reduce the energy consumption level in its buildings. This has taken the form of retrofits which increased the thermal resistance of building envelope by adding thermal insulation, storm windows and doors, and other measures. It has also taken the form of tightening up the building envelope to reduce energy lost through air leakage by infiltration and exfiltration.

For family housing units located near air field operations, an additional concern is reducing the interior noise level by increasing the sound attenuation of the building envelope. The Navy Family Housing Office recognized the need for investigating the combined beneficial effects of acoustical and thermal retrofits.

From a technical standpoint, there are several mutually beneficial effects resulting from combining thermal and acoustical improvements. For example, glass fiber is an excellent material for both reducing thermal conductance and increasing sound absorption. Also, control of air leakage (infiltration) through sealing of cracks is helpful in reducing sound transmission. In fact, one method of locating infiltration cracks is by an acoustic technique.

The thermal/acoustical performance of building components may be separated into three distinct properties:

1. Thermal conductance

2. Air leakage (infiltration) rate

3. Sound transmission loss

Thermal conductance is the heat energy transferred under the intluence of a temperature difference between the inside and the outside of the building component.

Air leakage or infiltration is the movement of conditioned and unconditioned air through a building envelope component. The motivation for air infiltration is a pressure difference that might be caused by wind and/or

temperature difference. Both conductance and infiltration represent energy losses through the building envelope; conductance through direct thermal transfer; leakage through loss of energy expended in conditioning air when exterior air brought into the building through infiltration replaces conditioned air lost through exfiltration.

Sound transmission loss is the measure of the effectiveness of a component in preventing high noise levels from being transferred through the element.

Many studies have developed technical information on the thermal conductance, air infiltration, and sound transmission of residential building components. A particularly valuable investigation was published in 1975 as a part of the NBS Building Science Series, No. 77: Acoustical and Thermal Performance of Exterior Residential Walls, Doors and Windows.(1) This study included data on 109 acoustical tests and 48 thermal tests on the performance of various combinations of walls, windows, and doors. Unfortunately, neither the NBS investigation, nor others, deal specifically with the improvement in thermal/acoustical performance that may be expected when various possible retrofit measures are added to structures that initially exhibit poor thermal/acoustical performance.

This investigation included a literature survey of possible retrofit procedures likely to improve the thermal/acoustical performance of residential building components. The literature survey was conducted in conjunction with a field survey of family housing units at a major Navy installation (Norfolk, Virginia). This was necessary to insure that proposed retrofits were compatible with existing typical Navy exterior wall housing construction.

On the basis of the above surveys, an investigation program was proposed which involved three typical residential wall and two roof/ceiling constructions, along with a series of retrofits designed to improve the thermal conductance, air leakage, and/or sound attenuation performance of the base construction. The base constructions and the retrofits to be applied were ultimately selected in conjunction with the Navy Family Housing Office on the basis of expected maximum benefit to retrofit cost for the three performance criteria.

Actual air leakage and sound transmission tests were conducted on the five basic constructions and the various retrofits. Thermal conductance values were calculated for most of the constructions and the retrofits. Where present thermal conductance data were felt to be inadequate, actual thermal conductance tests were performed.

Because of the present lack of general acceptance of metric units in the building construction industry, all data reported as a result of this investigation will be in U. S. customary units. The possibility of also including dual Metric SI units was considered but quickly discarded because of the very limited readership likely to be familiar with SI units and the added confusion caused by dual units.

The major portion of this work was funded by the Naval Facilities Engineering Command (NAVFAC) - Family Housing Office through the U. S. Army Corps of Engineers - Facilities Engineering Support Agency (FESA) at Ft. Belvoir, Virginia, Contract No. DAAK 70-78-D-0002, Task Order No. 18. During the course of the study, the program was expanded to cover four additional retrofits. This portion was covered by the Naval Construction Battalion Center at Port Hueneme, California, Contract No. N62583/82 M, Task Order 33.

ACKNOWLEDGEMENTS

Acknowledgement - The authors wish to express their appreciation for the assistance given by the members of the Manville Research and Development Center for their aid in implementing this investigation. Special credit is due David Floyd for his part in conducting the tests and calculating the results, Sylvia Martin for typing and editing the manuscript, and David Gladem for constructing the test assemblies.

Data - Original data developed in the course of this investigation are recorded in Manville Research and Development Center Contract Notebooks No. 32 and No. 33.

INVESTIGATION

Literature Survey

The purpose of the literature survey portion of the investigation was to provide candidate retrofit improvement measures that were likely to have the maximum benefit-to-cost ratio in terms of reduced thermal conductance, air leakage control and/or sound transmission.

The technical team working on this project considered themselves very well informed and already possessing a broad background in the fields of residential building construction, and generally available retrofits for improving thermal resistance and controlling air leakage of the envelope. Therefore, little literature search time was spent in these areas.

In the field of acoustics, two of the members of the technical team have had extensive experience in the general treatment of building acoustics, both sound absorption and sound transmission loss. However, none of this acoustical experience was directly related to the control of aircraft generated noise. This was the field in which the bulk of the literature survey phase of program was concentrated.

Twenty-nine references to investigations aimed at the control of aircraft noise in residences were examined. Many references dealt with the psychological and demographic aspects of aircraft noise; interior noise levels that most people would accept without undue adverse effects on their life style, in terms of excessive interference with sleeping, TV watching, phone conversation, etc. Other investigations dealt with the community noise levels around major airports; geographic surveys of outside noise levels resulting from aircraft operations, and in one case the estimated decrease in property values resulting from the proximity to an airport. Five references were found that had direct application to this project.

Under the Technical Studies Program of HUD/FHA, Bolt Beranek and Newman undertook a study of insulating houses from aircraft noise. The guide, published in November 1966, outlines a detailed procedure to be followed in

determining the necessary steps to improve the noise isolation of houses subject to aircraft generated noise. Tables are provided for estimating the noise levels from various types of aircarft under conditions of runup, takeoff and landing, with corrections for distance and direction. Three levels of noise isolation improvement are described: 5-10 perceived noise level (PNdB) units, 10-15 PNdB, and 15-20 PNdB.

The BBN guide suggests that windows are the weakest part of the exterior surface in most houses. Windows are therefore the place to start a noise control program, first by closing the window, second by improving the acoustical performance of the window. Since windows also provide ventilation and summer cooling, keeping windows closed usually implies installing an air conditioning system if one is not already present. While the estimated cost data in the BBN guide are obsolete, the construction details provided on noise control improvements are still very pertinent.

A study,(3) sponsored by the St. Louis Airport Authority, J. T. Weissenburger, et al, investigated the economic feasibility of retrofitting houses to improve their acoustical performance. The demonstration involved six houses located near the Lambert St. Louis International Airport. A variety of acoustical control measures were installed as remedial mesures for houses impacted by airport and aircraft noise. Major attention was devoted to improving primary weak areas - windows and doors. Other areas improved were exterior openings such as dryer vents, exhaust fans, and mailbox slots. Two houses were air conditioned; in two, the ceilings were improved; in one an independent wall was added. Retrofit costs (1981) ranged from $7,500 to $14,000, and averaged about $10,000. Exterior and interior noise levels were measured before and after retrofits were installed.

Weissenburger found that noise generated by an aircraft during takeoff was high in low frequency acoustic energy. On the other hand, high frequency energy was dominant during landing operations. Since low frequencies tend to interact more readily with the basic building structure, they were much more difficult to control. The standard improvements made to windows and doors were more effective against high frequency energy than against low frequencies. Replacing poor quality (in terms of air leakage) windows

with high quality double glazed units was effective. When the original window unit was single glazed and of good quality with a well fitted storm window spaced from it, the replacement with a double glazed unit was counter productive. The average effective noise reduction (ENR) after retrofit was about 30 dB. It was concluded that the measures taken were not sufficient to reduce interior noise from takeoffs to acceptable levels; more extensive modifications to the walls and roofs would be required.

NBS sponsored a critical review of the status in sound transmission through building structures, which also identified specific areas for further research.(4) B. H. Sharp, et al, of Wyle Research, Arlington, Virginia, conducted the investigation for NBS. They recognized three major noise transmission paths in the building envelope: (a) air infiltration (gaps, cracks and vents), (b) small wall elements (windows and doors), and (c) main panel elements (walls and roof). The mutually beneficial results between acoustical control and energy conservaton was pointed out, especially as related to air infiltration reduction; also cases where the synergism did not follow. Sealing of leaks to reduce air infiltration was felt to be the most cost effective measure for improving the acoustical performance, and should be performed first. When additional sound control was required, improvement of small wall elements and main panel elements should be undertaken in that order. An extensive bibliography of related references is included in the report.

The Los Angeles Department of Airports contracted with Wyle Laboratories, El Sequndo, California, for a series of investigations for control of noise in houses adjacent to the Los Angeles International Airport. The final report covering a soundproofing pilot project was issued in 1970.(5) Twenty inhabited houses were involved in the project. Three states of modification were studied: (1) minimum amount of added noise isolation, (2) intermediate amount, and (3) maximum amount. Stage 1 houses were modified to provide the owners with the option of living with doors and windows closed. Stage 2 houses required major modification of exterior doors and windows and beamed ceilings. Stage 3 houses required complete modification, including the additional treatment of roof/ceiling systems, floors and walls.

Stage 2 and 3 modifications generally produced results satisfactory to the homeowner, whereas Stage 1 did not. The degree of satisfaction achieved appeared to be more related to the amount of change rather than the absolute interior noise level after modification.

In a companion report, "Guide to the Soundproofing of Existing Homes Against Exterior Noise",[6] also issued in 1970, Wyle Laboratories describe details of construction that will provide Stage 1, 2 and 3 degrees of increased "soundproofing".

The Wyle guide also contains a section on the "Elements of Noise Control". This section covers the fundamentals, and emphasizes the importance of controlling the noise transmission through the acoustically weakest parts of the structure as the initial concern.

Field Survey

The objective of the field survey portion of the investigation was to insure that the details of the three wall and two roof/ceiling test panels to be constructed in the laboratory were representative of the construction found in Navy family housing units. It was not practical to inspect a statistically significant number of units due to the wide geographic spread of Navy operations. It was possible however to see representative units at a major Navy installation.

Arrangements were made for the investigation project manager to visit family housing units at the Navy base at Norfolk, Virginia. Through the cooperation of the local manager of housing, a facilities engineer was made available for a guide and two days were spent inspecting details of construction. Eighteen individual housing units from eight different projects were investigated at length. Original construction of the units spanned a time interval from 1940 to 1977.

Test Program

The scope of work statement in the original task order covering this investigation called for constructing three wall test assemblies and two roof/ceiling test assemblies,

and conducting sound transmission and air leakage tests on the basic construction and two retrofits of each test assembly. This totaled fifteen sound transmission and fifteen air leakage tests. In addition, two thermal conductance test assemblies were to be constructed, and thermal conductance determinations made on the basic construction and one retrofit of each (total of four thermal tests). Details of construction of each test assembly and retrofits were to be developed as part of the investigation.

During the course of the investigation four additional retrofits were added to the sound transmission and air leakage portions of the programs, making a total of nineteen each sound transmission and air leakage determinations in the whole program.

Test Constructions - On the basis of previous discussions with the Navy Family Housing Office, sponsor of the investigation, the construction details of the three wall and two roof/ceiling test panels had been generally agreed upon (see Table I).

TABLE I - GENERAL CONSTRUCTION DETAILS OF TEST PANELS

Panel	Type	Construction
A	Wall	Frame wall with plywood siding on slab-on-grade foundation and gypsum board interior
B	Wall	Frame wall with stucco exterior on crawl space foundation and gypsum board interior
C	Wall	Concrete masonry unit (block) wall with stucco exterior and gypsum board interior
D	Roof/Ceiling	Asphalt shingles on plywood deck on spaced trusses with gypsum board ceiling
E	Roof/Ceiling	Built-up roof on exposed deck with exposed beams

Construction details for the five test constructions were developed, along with proposed retrofits. The basis used for the basic constructions was the field survey of the Norfolk Navy base housing described above, and the past experience of the investigators with general residential construction practices during the 1950's and 1960's (when many of the Navy family housing units were built). Consideration was given to maximizing the amount of information that would be developed in the test program, i.e., test wall "A" was of frame construction over slab-on-grade foundation. while test wall "B" was of frame construction over a crawl space floor.

Special consideration was also given to window details, since past experience and the literature survey discussed above had shown that windows were a critical factor in the overall sound transmission properties of a residential wall. The window proposed for test wall "A" was a single glazed fixed sash; for test wall "B" a single glazed aluminum horizontal slider was proposed; for test wall "C" a single glazed double vent steel casement was suggested. While aluminum horizontal slider and steel casement windows have been found to be poor performers for both acoustic and air leakage considerations, they were very commonly utilized in DoD family housing construction of the period, including that for the Navy. All of the windows in the program were approximately three feet wide by four feet high. Since the total test wall for acoustical and air leakage tests was eight by fourteen feet, the window area was approximately eleven percent of the total wall area.

The proposed construction details of the five basic test panels, along with proposed retrofits are listed in Table II. The retrofits were selected on the basis of applicability and expected benefits. The major benefits expected are indicated in Table II as A - acoustic (increased sound attenuation), AL - air leakage, and T - thermal conductance. The priority order of proposed retrofits in Table II is on the basis of the ratio of anticipated benefit to the estimated cost of retrofit. Generally caulking and otherwise sealing is felt to be low in installed cost and yields significant benefits. Thus, caulking is usually the No. 1 priority retrofit.

TABLE IIa - PROPOSED TEST PANEL DETAILS - WALL A

Basic Construction

Slab on grade
5/8 inch texture 1-11 fir plywood siding (no sheathing)
2 by 4 studs, 16 inch OC (wall)
R-5 mineral fiber insulation
1/2 inch gypsum board
2 metal electrical boxes (with receptacles)
3-0 by 4-0 single glazed fixed wood sash

Possible Retrofits

Priority	Construction	Major Benefit Expected	Accepted for Test by NAVFAC
1	Caulk and seal window, lower plate, baseboard, electric boxes, siding	A, AL	X
2	Install interior secondary glazing (storm window) - 1/4 inch float glass	A, AL, T	X
3	Fur out interior of wall, add insulation (1-1/2 inch Zee stud, 1-1/2 inch (R-5) mineral fiber insulation, 1/2 inch gypsum board)	A, T	X
4	Fur out interior of wall, add insulation (adhesive applied 1-1/2 inch rigid polyurethane, R-12, or rigid polystyrene, R-8 board; adhesive applied 1/2 inch gypsum board)	T	

(See Appendix A for detail sketches and photographs of wall "A")

TABLE IIb - PROPOSED TEST PANEL DETAILS - WALL B

Basic Construction

Crawl space with 6 by 14 inch louvered vent
3/4 inch cement plaster stucco w/ chicken wire reinforcing
1/2 inch asphalt-saturated insulating board sheathing
2 by 4 studs 16 inch OC (wall)
R-5 mineral fiber insulation
1/2 inch gypsum board
2 metal electrical boxes (with receptacles)
3-0 by 4-0 single glazed aluminum horizontal slider sash
2 by 8 floor joists 16 inch OC
1/2 inch CDX plywood subfloor
1/4 inch hardboard underlayment.

Possible Retrofits

Priority	Construction	Major Benefit Expected	Accepted for Test by NAVFAC
1	Caulk and seal window frame, lower plate, baseboard, sill plate, electric boxes	A, AL	X
2	Install exterior secondary glazing (storm window)	A, AL, T	X
3	Add acoustical baffle to crawl space vent, insulate floor (R-11)	A, T	X
4	Fur out interior of wall, add insulation (adhesive applied 1-1/2 inch rigid polyurethane, R-12, or rigid polystyrene, R-8, board, adhesive applied 1/2 inch gypsum board)	T	

(See Appendix B for detail sketches and photographs of test wall "B"

TABLE IIc - PROPOSED TEST PANEL DETAILS - WALL C

<u>Basic Construction</u>

8 inch standard concrete block masonry unit
3/4 inch cement plaster stucco (exterior)
1 x 3 furring (no insulation)
1/2 inch gypsum board (foil-faced)
3 - 1 x 4 - 2 single glazed, double vent steel casement sash
2 metal electrical boxes (with receptacles)

<u>Possible Retrofits</u>

Priority	Construction	Major Benefit Expected	Accepted for Test by NAVFAC
1	Caulk and seal window frame, window sash	A, AL	X
2	Replace sash with double-glazed wood frame casement window	A, AL, T	X
3	Fur out exterior of wall, add insulation (1-1/2 inch thick rigid polystyrene board, stucco directly on polystyrene board)	T	X
4	Fur out interior of wall, add insulation (rigid polystyrene board, 1/2 inch gypsum board)	T	

(See Appendix C for detail sketches and photographs of test wall "C")

TABLE IId - PROPOSED TEST PANEL DETAILS - ROOF/CEILING D

<u>Basic Construction</u>

235 lb. self-sealing asphalt shingles
Double layer 15 lb. asphalt saturated felt
1/2 inch CDX plywood roof sheathing
6 inch diameter roof vent
2 x 4 wood truss, 24 inch OC, 3/12 pitch
R-7 mineral fiber insulation
1/2 inch gypsum board
1/4 inch plywood soffit
3/4 inch continuous eave vent with insect screening
22 x 30 inch attic scuttle
Recessed light fixture

<u>Possible Retrofits</u>

Priority	Construction	Major Benefit Expected	Accepted for Test by NAVFAC
1	Add insulation to ceiling (blown insulation to a total of R-19)	A, T	X
2	Add sound trap to roof vent	A	X
3	Seal ceiling openings (gasket scuttle, replace recessed ceiling fixture with surface mount)	A, AL, T	
4	Add suspended gypsum board ceiling with insulation (2 x 6 joists 24 inch OC; R-11 mineral fiber insulation)	A, T	X

(See Appendix D for detail sketches and photographs for test roof/ceiling "D")

TABLE IIe - PROPOSED TEST PANEL DETAILS - ROOF/CEILING E

Basic Construction

400 lb/square gravel or marble chips
3 ply hot mopped asphalt built-up roof
1 inch wood fiber insulation board
2 x 6 T&G exposed roof deck
2 - 2 x 12 exposed beams, 7-0 OC, 1/12 pitch

Possible Retrofits

Priority	Construction	Major Benefit Expected	Accepted for Test by NAVFAC
1	Caulk and seal (seal openings around exposed beams and outside wall)	A, AL	X
2	Add dropped ceiling between exposed beams (R-19 mineral fiber insulation, 2 x 4 joists 24 inch OC, 1/2 inch gypsum board)	A, T	X
3	Add insulation to top of deck (remove gravel, add rigid insulation, add new built-up roof and gravel)	T	

(See Appendix E for detail sketches and photographs of roof/ceiling"E")

The final selection of constructions to be included in the test program was by the NAVFAC - Navy Family Housing Office, as a result of joint discussions with that office. Those retrofits accepted (both the initial program and the program extension) are indicated in Table II.

Test Panel Construction - All panel constructions tested in this investigation were fabricated at the Manville Research and Development Center, Denver, Colorado. The same panels were used for sound transmission and air leakage determinations. These were generally 8 by 14 feet in size. Where required, separate thermal conductance test panels were prepared which were 5 feet, 4 inches by 6 feet, 8 inches overall, with a test area 2 feet, 8 inches by 4 feet, 0 inches. The objective in constructing the test panels was to make them functionally true prototypes of the real construction including finish details such as electrical outlets and window treatment.

The majority of the constructions were assembled by an outside carpenter/remodeling subcontractor, with assistance from Manville technician personnel. For specialty trades such as block masonry and stuccoing, outside subcontractors skilled in these areas were brought in. Materials required were purchased through normal trade channels. In the case of roofing and insulation, some of the materials used were of Manville manufacture but most were not. All construction took place under the close supervision of technical personnel responsible for this project.

Test Wall Construction "A" - Construction "A" represents a frame wall with 2 by 4 studs, 16 inch OC, on a slab-on-grade foundation. In an investigation of the air infiltration characteristics of 50 Texas houses, Caffey found that the sole plate was the largest single location for air leakage, accounting for 25 percent of the total leakage on the average.(7) The second most important location for air leakage Caffey found to be wall electrical outlets, accounting for 20 percent of the total leakage.

In the construction of test wall "A", the irregularities of the top surface of the slab were simulated by using solid concrete masonry units as a foundation (which also provided a low sound transmission path for this portion of the wall). Two wall mounted electrical receptacles were incorporated in the construction of wall "A", as was done for the other wall constructions. The space between the

outlet boxes and surrounding gypsum board was approximately 1/16 - 1/8 inch representing typical field construction.

Test wall "A" was finished on the exterior with 5/8 inch thick texture 1-11 plywood siding. As is customary with the use of this siding material, the sheathing was omitted. The interior of the wall was finished with 1/2 inch thick gypsum board, with the joints taped and spackled, and the nail heads dimpled and spackled. The wall cavity was insulated with an R-5 mineral fiber insulating batt with attached vapor barrier. This was installed adjacent to the back surface of the siding.

The fixed sash window frame was shop fabricated of wood, with double strength single glazing installed with sealant and wood stops (refer to Figure A2).

The initial retrofit (A1) consisted of caulking and sealing, which was done in stages so that individual effects could be observed.

The second retrofit (A2) consisted of installing secondary glazing in the form of a storm sash. Because of the location of the prime fixed window, the storm was installed inside. The unit selected had an aluminum subframe (which was permanently installed) and a removable glazed section which was attached to the subframe by means of thumb screw (refer to Figure A7). In order to maximize the sound attenuation resulting from installation of the secondary glazing, 1/4 inch thick float glass was utilized with the maximum spacing practical between the glazings (inches). Suggested was the possibility of a further improvement in the sound attenuation properties by installing sound absorbing material in the cavity, between the glazings.[8] This was also tried.

The third retrofit (A3) consisted of furring out the interior wall (refer to Figure A8). One and one-half inch Zee studs were installed horizontally 24 inch OC, placing 1-1/2 inch mineral fiber insulation between the studs (which functions as both sound absorber and thermal insulation) and installing a second layer of 1/2-inch gypsum board which was also taped and spackled.

For most of the basic constructions, and the subsequent retrofits it was possible to calculate the overall thermal transmittance of the component with reasonable accuracy,

using the procedures outlined in the ASHRAE Handbook of Fundamentals.[9]

In the case of wall retrofit "A3", the effect of the cross-furring on the framing member thermal conductance was not readily calculable. Actual thermal conductance tests were performed on this construction.

Additional construction details of wall test "A" and its retrofits, including typical sections and photographs, are located in Appendix "A". Also see Appendix "F" for details of the thermal conductance test panel.

Test Wall Construction"B" - Construction "B" represents a frame wall of 2 by 4 studs 16 inch OC erected on a crawl space type foundation. The exterior was finished with a 3/4 inch thick cement plaster stucco, applied in two coats, with chicken wire reinforcing over 1/2 inch thick asphalt saturated insulating board sheathing. The interior of the wall was finished with 1/2 inch thick gypsum board, which was taped and spackled. The wall was insulated with R-5 mineral fiber insulation. Since this insulation product is no longer regularly manufactured for residential applications, it was fabricated by cutting a current product down to 1-1/2 inch thickness by means of a horizontal band saw. The wall also had two electrical receptacles. A space of approximately 1/16 -1/8 inch was maintained between the outlet boxes and gypsum board to simulate typical field conditions of installation.

The window installed in test wall "B" was a single glazed aluminum framed horizontal slider type. When the initial air leakage determinations of test wall "B" produced anomalous results, the manufacturer of the window unit was contacted. It developed that the unit originally installed was not the proper type for the application, and another one was furnished and reinstalled. While very consumptive of both time and effort, the experience did demonstrate dramatically the sensitivity of the amount of air leakage to window fit and adjustment, especially of the horizontal slider type.

The first retrofit (B1) also consisted of caulking and sealing. As before, this was accomplished in stages in order to observe the separate effects produced.

The second retrofit (B2) consisted of installing a storm window unit on the outside of the prime window unit (refer to Figures B7 - B9). The storm unit was custom fabricated to dimensions furnished by a manufacturer whose business consists of furnishing similar units to the local storm window installer trade.

The third retrofit consisted of acoustically treating the crawl space. An acoustical baffle or sound trap (refer to Figures B7 - B9) was added to the crawl space vent. The subflooring was temporarily removed. R-11 kraft paper faced mineral fiber insulation was installed from the top by side stapling to the joists, which provided both thermal insulation for the floor and sound absorption in the crawl space area.

Additional details of test wall "B" construction and its associated retrofits, including a typical section and photographs, are located in Appendix "B".

Test Wall Construction "C" - Construction "C" represents a block wall of 8 inch standard concrete masonry units (CMU). The exterior was finished with a two-coat cement plaster stucco of about 3/4 inch total thickness, reinforced with 1 inch "chicken wire" mesh. The interior was finished by installing 1/2 inch foil-faced gypsum board on 1 by 3 nominal wood furring. The gypsum board was taped and spackled. Except for the thermal resistance offered by the open cores of the concrete masonry units and the foil facing of the gypsum board, the wall was otherwise not insulated.

A single glazed double vent steel casement window unit, 3 feet, 1 inch by 4 feet, 2 inches, was installed in construction "C" (reference Figures C3 - C5). While very commonly used in residential construction of the 1950's, steel sash are now obsolete for new construction, having been largely supplemented by aluminum sash. After some investigation a manufacturer was located in California, who had purchased the remaining stock, and jigs and fixtures of Hope's Windows, when they discontinued that business. The window unit had a thin plastic foam gasket which sealed the movable casement sash. Under the assumption that this gasket would no longer be in place, after 25 years or more of service, the wall was tested both with and without the gasket. The steel sash was installed in the CMU wall in accordance with Navy Family Housing Unit standard practice

for this type of construction. The window opening was formed on the sides with "sash" block. A wood spline was inserted in the sash block recess, with the steel sash unit screwed to the spline. The window opening was finished on the exterior with stucco returns on the sides and top, and a brick sill on the bottom. On the interior, gypsum board returns completed the top and sides, with a wood stool.

The wall had two steel electrical boxes with receptacles installed. It was assumed that the associated electrical wiring would be supplied through the top of the wall, from the attic space. A space of approximately 1/16 - 1/8 inch was maintained between the outlet boxes and surrounding gypsum board to simulate typical field installation.

The first retrofit (C1) also consisted of caulking and sealing. As before, this was accomplished in stages, in order to observe the separate effects produced.

The second stage retrofit (C2) consisted of replacing the steel sash window unit. Originally it was proposed to install a double glazed wood framed casement unit. An investigation of recent developments in the replacement window market showed that double glazed aluminum replacement window units of "thermal break" construction are now available. In addition to being less costly than the wood framed replacement units, the aluminum uniuts are readily available in custom sizes of 1/2 inch increments of width and 1 inch increments of height. Thus, adaptation of the replacement units to an existing opening is greatly simplified. Also included in the market study were vinyl framed replacement window units, which did not appear attractive due to unresolved questions of service under adverse temperature conditions. On the basis of the above, permission was secured to substitute a double glazed, thermal-break type, single-hung aluminum replacement window for the wood unit originally considered for retrofit "C2" (refer to Figure C6). Through the cooperation of the local replacement window manufacturer, and an agreement to share related information developed, a triple glazed window unit was also tested. This consisted of the double glazed replacement window plus a pair of removable storm window units.

Retrofit "C3" (refer to Figures C7 - C8) consisted of adding exterior thermal insulation to the wall. This was accomplished by installing 2 by 2 nominal wood furring,

vertically 24 inches on center. The space between the furring was filled with 1-1/2 inch thick extruded polystyrene foam insulation board. This was covered with 3/4 inch cement plaster stucco, applied in two coats and reinforced with 1 inch chicken wire mesh. The brick window sill was also replaced.

Additional details of test wall "C" construction and its associated retrofits, including a typical section and photographs, are located in Appendic "C".

Test Roof/Ceiling Construction "D" - Construction "D" represents conventional truss type roof/ceilings. Half trusses, with a pitch of 3/12 and comprised of 2 by 4 chords were erected 24 inches on center. The roof was sheathed with 1/2 inch CDX plywood, and covered with 2 layers of 15 pound asphalt saturated felt and 235 pound (per square of 100 square feet) self-sealing asphalt three tab shingles.

The attic space was insulated with R-7 mineral fiber batt type insulation. Ventilation was provided in the form of a 6 inch diameter roof vent near the ridge and continuous 3/4 inch wide eave venting in the plywood soffit. The latter was covered with insert screening.

The interior was finished with 1/2 inch gypsum board, which was taped and spackled. A 22 by 30 inch scuttle was installed to provide access to the attic space, as required by most codes. The scuttle was closed by a removable piece of 1/2 inch gypsum board, with a loose mineral fiber insulation batt on top. The ceiling also included an 8 inch diameter flush mounted, Edison type E7070P recessed light fixture with removable glass lens assembly. This was installed within the National Electrical Code requirements of 3 inch insulation clearance around the fixture.

The first retrofit (D1) called for adding insulation to the ceiling insulation already in place to a total thermal resistance of approximately R-19. This was installed pneumatically by blowing loose mineral fiber insulation. An attempt was made to maintain clearance below the roof sheathing for eave ventilation. As is universally the case in the field, the attempt was not completely successful.

The second retrofit (D2) required installation of a sound trap on the ridge located attic roof vent. The roof vent

was completely blocked acoustically, which was found to have no effect on the overall sound transmission properties of the roof/ceiling assemnbly. Therefore. no further investigation of installing a sound trap at this location was justified.

Retrofit designation D3 as proposed to NAVFAC was not approved for testing. Therefore, no description or test data are provided for this designation.

In the third retrofit (D4) a second independently suspended ceiling was installed. Two by six nominal ceiling joists, 24 inch on center, were attached to the sidewalls, and supported the 1/2 inch gypsum board ceiling. The latter was taped and spackled. The joists were spaced approximately one inch below the existing gypsum board ceiling surface. The recessed light fixture was removed (hole in the initial ceiling was patched). An improved design attic scuttle, with a plywood face, gasketed seal and positive closure means was installed in the suspended ceiling. R-11 mineral fiber batt type insulation with kraft paper vapor barrier attached plus an additional 4 mil polyethylene vapor/air barrier was installed in the space between the two ceiling surfaces.

Additional construction details of roof/ceiling test "D" and its retrofits, including typical sections and photographs, are located in Appendix "D".

Test Roof/Ceiling Construction "E" - Construction "E" represents a low-slope roof/ceiling, with exposed beams and decking, commonly found in "Capehart" funded military family housing. The deck consisted of exposed nominal 2 by 6 T&G vee joint wood decking. This was supported by exposed double nominal 2 by 12 wood beams installed 7 feet, 0 inch on center with a 1/12 pitch. One by two and 1 by 3 nominal wood furring were installed as beam and eave trim, and beam closure pieces respectively.

One inch of wood fiber board insulation was nailed to the top surface of the deck. A three ply built-up roof with hot mopped asphalt and gravel surface (approximately 400 pounds per square of 100 square feet), completed the construction.

The first retrofit (E1) consisted of caulking the many openings around the exposed beams and wall section between

the beams. As an additional measure, mineral fiber batt type sound absorption material was added to the wall cavity, between the beams.

For retrofit "E2" a suspended ceiling was installed, between the exposed beams. The intent was to improve both the sound transmission attenuation and the thermal conductance performance of the roof/ceiling, while retaining the exposed beam as a desirable architectural feature. Nominal 2 by 4 wood ceiling joists were installed 24 inch on center, and spaced 6-1/2 inches below the bottom surface of the roof deck. R-19 mineral fiber batt type insulation with separate continuous 4 mil polyethylene film vapor/air barrier was installed. A 1/2 inch gypsum board ceiling, which was taped and spackled, completed the retrofit. About 5 inches of exposed beam and trim was retained below the dropped ceiling plane.

Because of uncertainties in calculating the overall thermal conductance of construction "E", with exposed beams acting as heat transfer fins with retrofit "E2", thermal conductance tests were performed on this construction also.

Additional construction details of roof/ceiling test "E", including typical sections and photographs, are located in Appendix "E". Also see Appendix "F" for details of the thermal conductance test panel.

Sound Transmission Test Procedure - The test method followed to determine the sound transmission properties of the various constructions was ASTM E90-75, "Standard Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions".(10) The various wall constructions were installed in turn in the 9 by 14 foot opening separating the "source" acoustical reverberation chamber from the "receiving" reverberation chamber. See the previous discussion and Appendices A-C for construction details of the various walls tested.

Both constructions "D" and "E" involved testing roof/ceiling assemblies, which are normally horizontal. Since the opening in the sound transmission test facility was vertical, some type of adaptation was necesssary. Constructing and testing of roof/ceiling assemblies in the vertical plane was considered and discarded, since there was insufficient assurance that the elements would perform in similar fashion when oriented vertically. Also, the

was insufficient assurance that the elements would perform in similar fashion when oriented vertically. Also, the prospects of constructing a built-up roof with gravel surfacing, while in the vertical position were unattractive to say the least. Instead, a temporary stub wall of high sound attenuation properties was constructed. This permitted the roof/ceiling assemblies to be constructed and tested in their normal orientation. See Appendix G for details of the construction of this wall. Also see the previous discussion and appendices D and E for construction details of the two roof/ceiling assemblies tested.

While the contract obligated performing a total of nineteen sound transmission tests, it was felt that much more useful information could be developed if tests were conducted on each increment of a retrofit, rather than for the retrofit as a whole. In order to accomplish this, and still stay within the time budget allotted for the sound transmission tests, it was necessary to develop a computer program which automatically supervised the various phases of a transmission loss (TL) test without the need for continuous manual supervision. With this aid it was possible to conduct 60 TL determinations during the course of this investigation.

Transmission loss (TL) varies with the frequency of the sound waves striking the specimen surface. As a result, a complete characterization of the TL performance requires that measurements be made over a wide range of frequencies. Under this program, measurements were made in one-third octave wide bands with center frequencies ranging from 100 to 5000 Hz or cycles per second.

Based on the TL for each 1/3 octave frequency for the range from 125 Hz through 4000 Hz inclusive, the sound transmission class (STC) of each construction was calculated. The procedure described in "Standard Classification for Determination of Sound Transmission Class", ASTM E413-73[11] was followed. STC provides a single number rating for comparing the transmission loss performance of various partitions. It was designed to correlate with subjective impressions of speech sound isolation in offices and dwellings. It was not designed for other applications with sound spectra differing widely from human speech, such as industrial, highway and aircraft generated noise. In spite of this serious limitation it was decided to include STC data, since it is a term

generally understood by those familiar with building construction component performance.

See Appendix G for a detailed description of the sound transmission loss test procedure and test facilities, and a discussion of error analysis.

Air Infiltration Test Procedure - The test method followed to determine the air leakage performance of the various constructions was ASTM E283-73, "Standard Test Method for Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors".[12]

The same constructions used for sound transmission loss determination were also tested for air leakage. The "source" side reverberation chamber was reasonably air tight initially; by sealing and caulking it was further improved. A temporary closure was fitted to the entry opening to the "source" side chamber. Means were provided for maintaining the "source" side chamber (exterior face of the partition tested) at a constant air pressure relative to the interior surface, and simultaneously determining the volume of air required to hold the pressure constant. Initially the chamber leakage rate was determined as a function of pressure differential by sealing off the test wall with impermeable plastic film. By subtracting the chamber leakage from the total volume of air, the net air leakage through the partition under test was determined as a function of the pressure differential.

Air leakage determinations were generally made at five differential pressures ranging from 0.1 to 0.3 inches water for both positive and negative pressure differential. Positive pressure means that the absolute pressure on the interior side of the partition under test was higher than that on the exterior side. (Air leakage measurements were made originally with positive denoting the pressure on the "source" room or exterior side of the partition; in reporting the data the polarity was reversed to conform to that of other investigators, where positive denotes interior pressure greater than that on the outside.)

Air leakage measurements were corrected to standard conditions 29.92 in. Hg (barometer), 69.4^{o}F (temperature), and 0.075 lb./ft^3 (air density) as per the requirements of ASTM E283. As with sound transmission loss determinations, it seemed desirable to measure the

incremental effects on the air leakage rate of the increments of the various retrofits. While nineteen sets of air leakage rate data would have satisfied the requirements of the contract, including the program extension, fifty-five sets of air leakage determinations were actually performed during the course of this investigation. This was possible in part because a computer program was developed which calculated the linear regression for the log of the air flow versus the log of the differential pressure, and then interpolated air leakage rates at even differential pressures. The value of net air leakage rate (total air flow less chamber leakage) is reported at a differential pressure of +0.3 and -0.3 in.H_2, as per the requirements of ASTM E283. This pressure is equivalent to that developed by a wind speed of 25 miles per hour.

See Appendix H for additional details of the air leakage rate test procedure and test facilities, and a discussion of the error analysis.

Thermal Conductance Test Procedure - The test method followed to measure the thermal conductance of four of the constructions was ASTM C-236, "Standard Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box".[13]

The thermal conductance of most of the constructions, including retrofits, was calculated using the procedures described in the ASHRAE Handbook of Fundamentals.[9] As discussed above, in the case of retrofits "A3" and "E2", these procedures were not felt to be sufficiently precise and actual determinations of thermal conductance were made of both the basic construction and the retrofit.

The guarded hot box test facility has a metering area of 32 by 48 inches, with an overall test panel area of 64 by 80 inches. Test panels of these dimensions were constructed (see Appendix F for details of construction). In the case of test panel "E", with exposed decking and exposed beams, it was necessary to "scale" the thickness of the beams in order to model faithfully the construction. In practice the exposed beams consist of a pair of spaced nominal 2 by 12's (actual thickness 1-1/2 inches) installed at approximately 6 to 8 feet on center. Since the maximum dimension of the test area is 4 feet, the thickness of the pair of beams in the thermal test panels was also cut in half.

In the case of the acoustical tets on construction "E", the panel tested including an actual 3 ply built-up roof, constructed with hot-mopped asphalt and complete with pea gravel surface, since it was felt that the construction and mass of the assembly would have a direct bearing on the acoustical performance of the assembly. In the case of the thermal performance tests on construction "E", a prepared roofing membrane was substituted; it has similar thermal performance and made the assembly much lighter and thereby easier to handle.

The thermal conductance tests were conducted at an approximate mean temperature of 45°F, representing typical winter conditions of about 70°F on the hot surface of the panel and 20°F on the cold surface.

See Appendix I for further details of the guarded hot box test procedure and a description of the test facility.

Test Results

The results of the acoustical and the air leakage tests on the various constructions are tabulated in Table III.

The sound attenuation is given in terms of the Sound Transmission Class (STC). While a single number rating, such as STC, does have serious limitations, it is widely recognized and is convenient. Because of the limitations of the STC rating, actual transmission loss (TL) data in decibels (dB) are shown as a function of frequency in Figures 1 through 10. The frequency range covered is 100 to 5000 Hz by 1/3 octave band widths.

It should be noted that both transmission loss and STC rating are scales, expressed in dB. A change logarithmic of 3 dB represents a change in sound power attenuation by a factor of 2, 6 dB equals a factor of 4, 9 dB is a factor of 8, 10 dB is a factor of 10, etc. A change of 3 dB is just perceptible to the human ear; a change of 10 dB is perceived as half (or twice) as loud.

The air leakage rate is given in terms of the volume of air flow under standard conditions with a positive and a negative pressure differential of 0.3 in. H_2O. This pressure differential is equivalent to the static pressure developed by a 25 mile per hour wind. While these data are reported to the nearest 0.1 CFM, this level of precision is of doubtful significance except for comparative purposes.

The measured thermal conductance data for the four panels tested are shown in Table IV for typical winter conditions. The average test panel surface temperatures were approximately 70°F on the hot side, 20°F cold side, and 45°F mean. The "R value" tabulated is the total overall thermal resistance of the panel, and is quoted in units of hr·sq ft°F/Btu.

The "C-Value" is the panel thermal conductance, and is numerically the reciprocal of "R-value" or thermal resistance. "C-value" is expressed in units of Btu/hr.sq ft.°F. The "U-Value" is the overall thermal transmittance of the assembly. It is similar to and has the same units as "C-value". However "U-value" considers the overall air-to-air thermal performance, and includes the air film thermal resistances on both the exterior and interior surfaces in addition to the thermal resistance of the panel itself. Thus "U-value" is always lower than "C-value".

TABLE IIIa - ACOUSTICAL AND AIR LEAKAGE TEST RESULTS - WALL "A"

Test	Retrofit	Construction	Sound Trans-mission Class	Air Leakage - CFM at 0.3" ΔP Positive	Negative
1	-	Base wall construction	32	66.5	66.3
2	A1	Caulk Interior Window Frame	33	59.5	58.6
3	A1	Caulk Baseboard		31.8	32.9
4	A1	Both 2 and 3 Combined		10.6	11.9
5	A1	Repeat of 4	35	10.3	11.0
6	A1	5 plus 2 Electrical Receptacles Sealed with Foam Gaskets	35	7.4	8.1
7	A1	6 Plus Receptacles also Plugged		5.5	6.4
8	A1	7 Plus Exterior Caulked	35	0.3	0.8
9	A2	8 Plus 1/4 Inch Interior Storm Added	38		
10	A2	9 Plus Sound Absorption Added to Window Cavity	38		
11	A3	8 Plus Interior Wall Furred 1-1/2 Inch and Insulated	38		
12	A2/3	Both 9 and 11 Combined	47		
13	-	Same as 11 with Window Acoustically Blocked	47		

TABLE IIIb - ACOUSTICAL AND AIR LEAKAGE TEST RESULTS - WALL "B"

Test	Retrofit	Construction	Sound Trans. Class	Air Leakage - CFM at 0.3" _P Positive	Negative
1	-	Orig. Window - Window open	13		
2	-	Same as 1 - window closed, unlocked	29	57.2	37.9
3	-	Same as 1 - window closed, locked	28	74.1	49.0
4	-	Window adjusted - window closed, unlocked	29	31.1	36.4
5	-	Same as 4 - window closed, locked	28	43.8	48.8
6	-	Window replaced - window closed, unlocked	29	38.4	38.7
7	-	Same as 6 - window closed, locked	29	38.0	40.0
8	B1	Same as 7 - wall caulked & sealed	30	22.4	29.6
9	B1	Same as 8 - latch adjusted	30	16.4	23.7
10	B2	Same as 8 - storm sash installed	38	19.9	25.4
11	-	Same as 8 - window openings taped/sealed	39	6.1	10.4
12	-	Window blocked	46	5.1	8.8
13	B3	Same as 12 - crawl space acoustically treated; floor reinstalled	49	6.0	9.8
14	-	Sames as 13 - floor joints taped		0.3	
15	-	Same as 13 - crawl space vent blocked and sealed	49		

TABLE IIIc - ACOUSTICAL AND AIR LEAKAGE TEST RESULTS - WALL "C"

Test	Retrofit	Construction	Sound Trans-mission Class	Air Leakage - CFM at 0.3" _P Positive	Negative
1	-	Base Wall Construction	24	172.3	115.8
2	-	Lock Sash	25	103.1	100.2
3	C1	Gasket Sash	27	116.3	50.4
4	C1	Gasket & Lock Sash	30	36.0	33.8
5	C1	4 Plus Seal Top Sill Elect. Wire Holes	30	19.2	14.8
6	C1	4 Plus Caulk Baseboard	35	32.5	
7	C1	6 Plus Seal Elec. Outlets		30.5	
8	C1	7 Plus Caulk Window Frame	30	17.1	
9	C1	4 Plus Seal all Above	30	15.5	14.1
10	C2	Install Double Glazed Aluminum Single Hung Replacement Sash Unit	37	0.6	1.7
11	C3	10 Plus Fur Outside Wall, Insulate and Restucco	39		
12	C2	Same as 11 but Interior Storm Window Added (Triple Glazed)	39		
13	C2	Same as 12 but Window Acoustically Blocked	52		

TABLE IIId - ACOUSTICAL AND AIR LEAKAGE TEST RESULTS - FLOOR/CEILING "D"

Test	Retrofit	Construction	Sound Transmission Class	Air Leakage - CFM at 0.3" ΔP Positive	Negative
1	-	Base Roof/Ceiling with Open Recess Light and Conventional Scuttle	43	73.9	66.5
2	-	Replace Scuttle with Solid Gypsum Board		44.3	45.6
3	-	1 Plus Install Lens Recess Light		34.8	26.3
4	-	Both 2 and 3 Combined	43	5.2	5.4
5	D2	4 Plus Block Roof Vent	43		
6	D1	Remove Recess Light and Add Attic Insulation	47		
7	D1	6 Plus Block Eave Vent Strip	49	30.5	
8	D4	Install Dropped Insulated Ceiling w/ Improved Scuttle (no Recessed Light)	57	15.5	15.5
9	D4	8 Plus Replace Open Cell Foam Tape Seal w/ Closed Cell Foam	59	2.8	2.9
10	D1/4	9 Plus Added Insulation in Attic	60		

TABLE IIIe - ACOUSTICAL AND AIR LEAKAGE TEST RESULTS - CEILING "E"

Test	Retrofit	Construction	Sound Transmission Class	Air Leakage - CFM at 0.3" ΔP Positive	Negative
1	-	Base Roof/Ceiling Construction	41	29.7	36.5
2	-	Sound Absorption in Beam Closure	42		
3	E1	Same as 2 Plus Exterior Caulked		1.3	0.9
4	E1	Same as 3 Plus Interior Caulked	46	0.3	0.0
5	E2	Add Suspended Insulated Ceiling	51		

TABLE IV - THERMAL CONDUCTANCE TEST RESULTS

	Hot Surface °F	Cold Surface °F	Mean Temp. °F	Thermal Performance "R"*	"C"**	"U"** ***
Wall "A" - plywood siding on 2 by 4 frame, gypsum board interior, R-5 Insulation	68.8	21.9	45.3	6.95	0.144	0.130
Wall "A" plus retrofit, A3 - 1-1/2 inch steel Zee cross furring, R-5 insulation added	70.1	21.0	45.6	12.4	0.081	0.075
Roof/ceiling "E" - Built-up roof on one inch wood fiber board insulation on exposed T&G deck and beams	66.6	18.7	42.6	5.70	0.175	0.150
Roof/ceiling "E" plus retrofit E2 - suspended ceilings, R-19 insulation added	70.1	16.8	43.4	20.1	0.050	0.047

* hr sq ft °F/Btu
** Btu/hr sq ft °F

*** Includes effects of surface air film resistances.

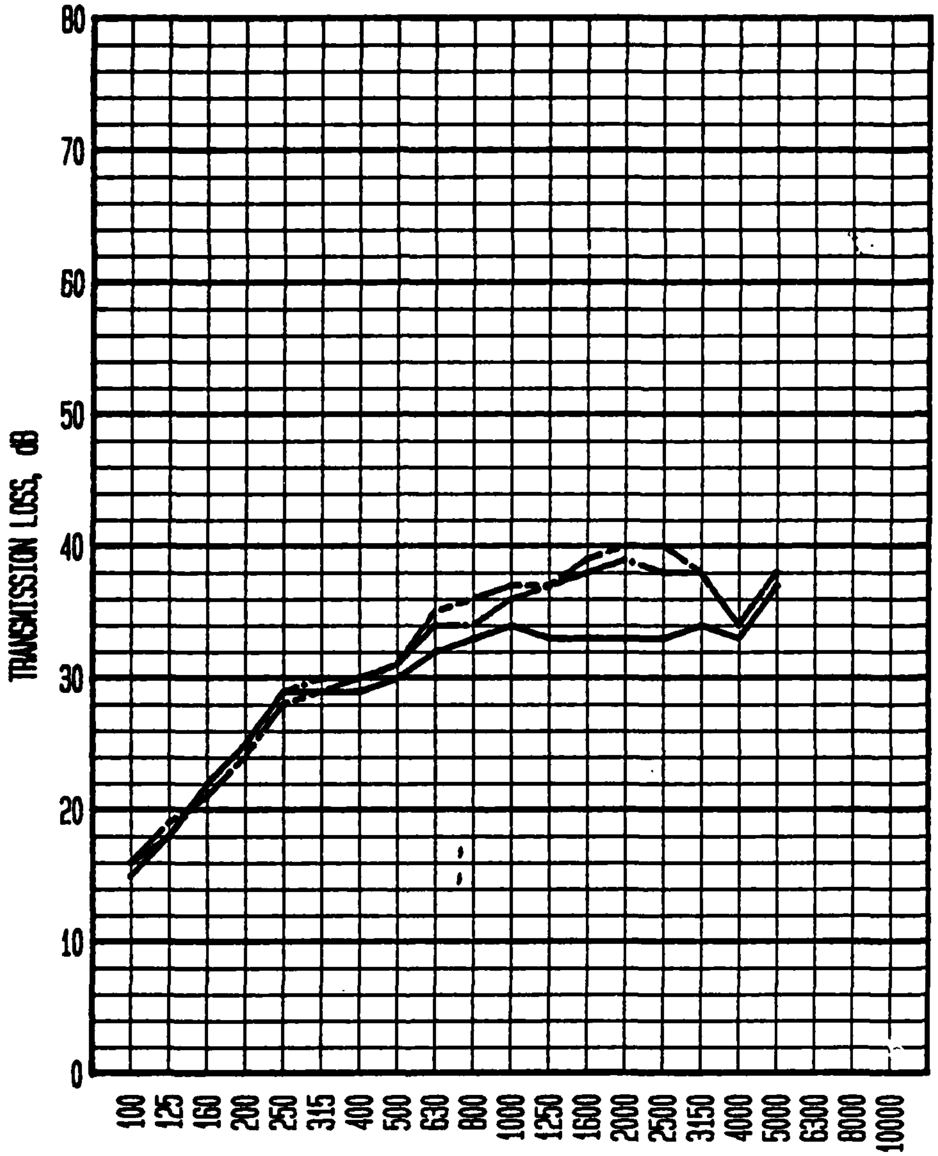


FIGURE 1. TRANSMISSION LOSS, WALL "A"

———————	ORIGINAL CONSTRUCTION	STC=32
———·———	INTERIOR CAULKED AND SEALED	STC=35
— — — — —	EXTERIOR AND INTERIOR CAULKED AND SEALED	STC=35

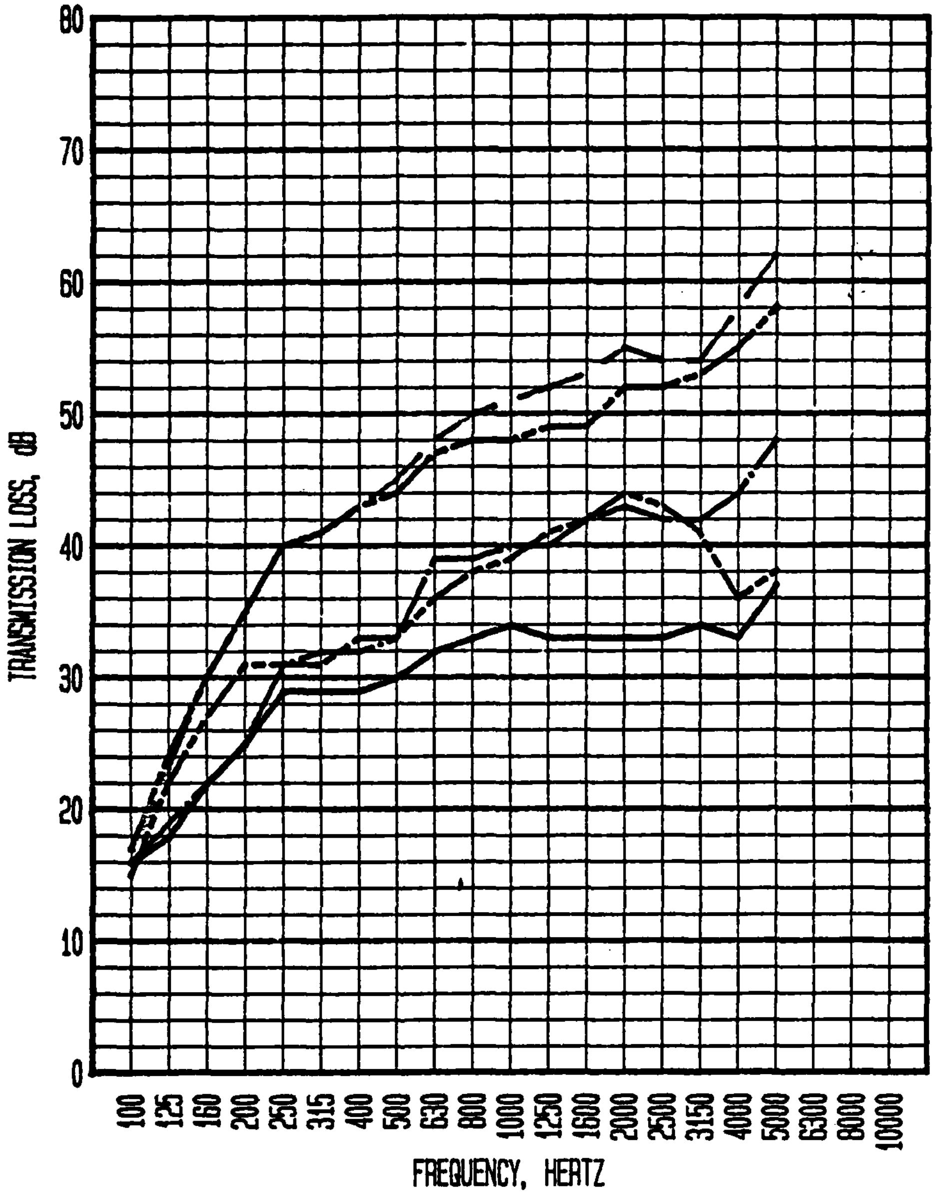


FIGURE 2. TRANSMISSION LOSS, WALL "A"

———————	ORIGINAL CONSTRUCTION	STC=32
———·———	PLUS 1\4" INTERIOR STORM WINDOW	STC=38
- - - - - - -	INTERIOR FURRED 1-1\2" PLUS INSULATION	STC=38
——— - ———	STORM WINDOW PLUS FURRED WALL	STC=47
——— ———	FURRED WALL PLUS WINDOW BLOCKED	STC=47

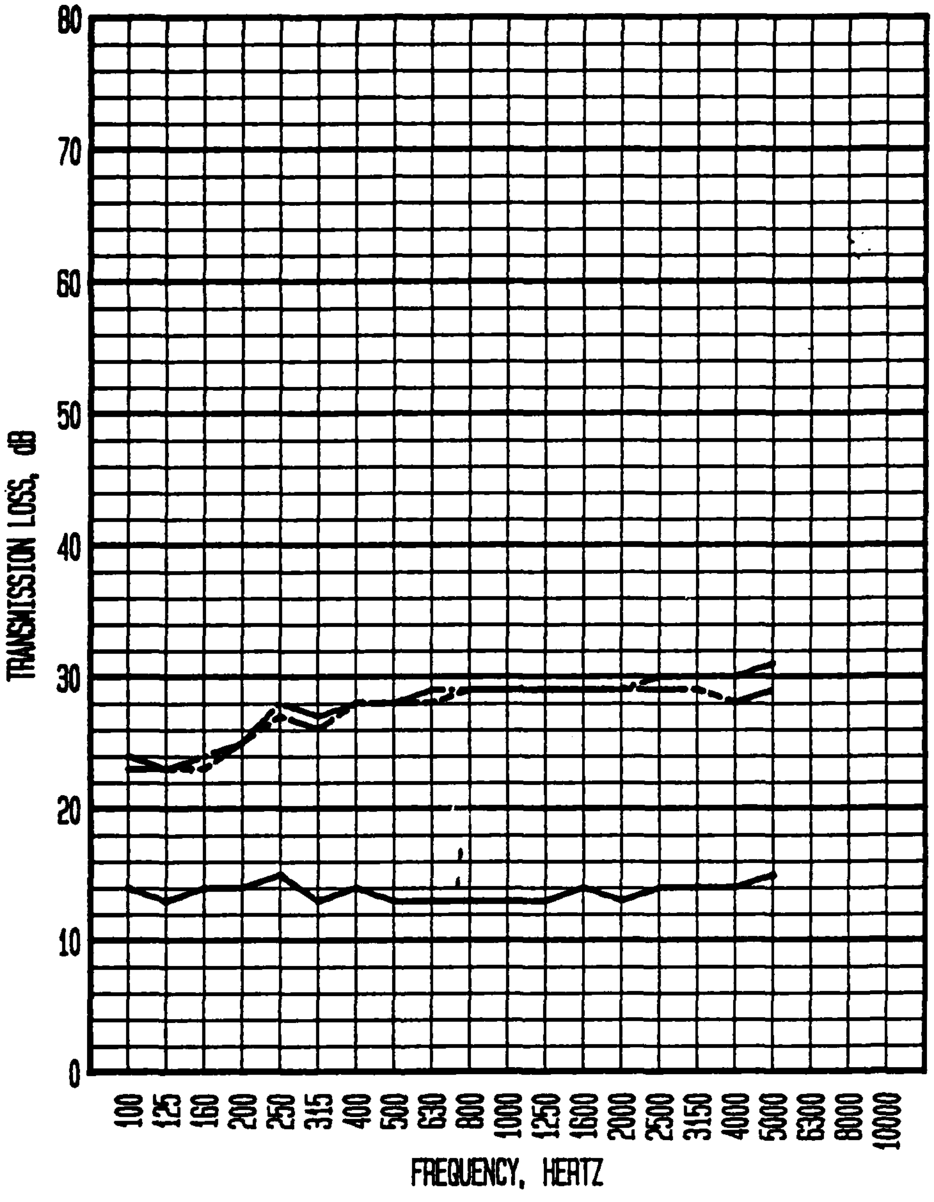


FIGURE 3. TRANSMISSION LOSS, WALL "B" WITH ORIGINAL WINDOW

————	WINDOW OPEN (NO SCREEN)	STC=13
——·——	WINDOW CLOSED (UNLOCKED)	STC=29
—-—-—	WINDOW CLOSED (LOCKED)	STC=28

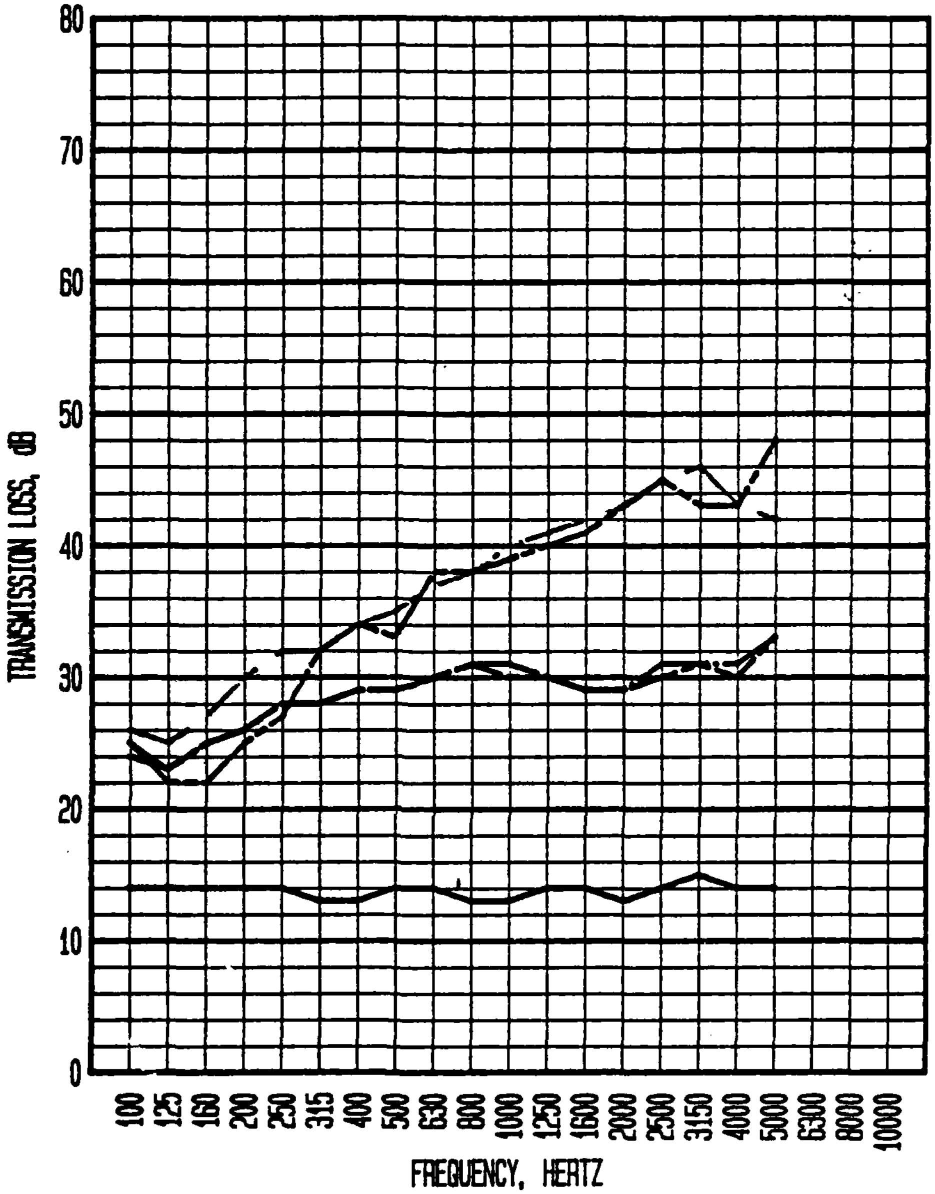


FIGURE 4. TRANSMISSION LOSS, WALL "B", WITH REPLACEMENT WINDOW

———————	WINDOW OPEN (WITH SCREEN)	STC=13
———·———	WINDOW CLOSED (LOCKED)	STC=30
——-——-——-	WINDOW FRAME CAULKED	STC=30
———-———-	EXTERIOR STORM WINDOW ADDED	STC=38
——— ———	WINDOW UNIT COMPLETELY SEALED	STC=39

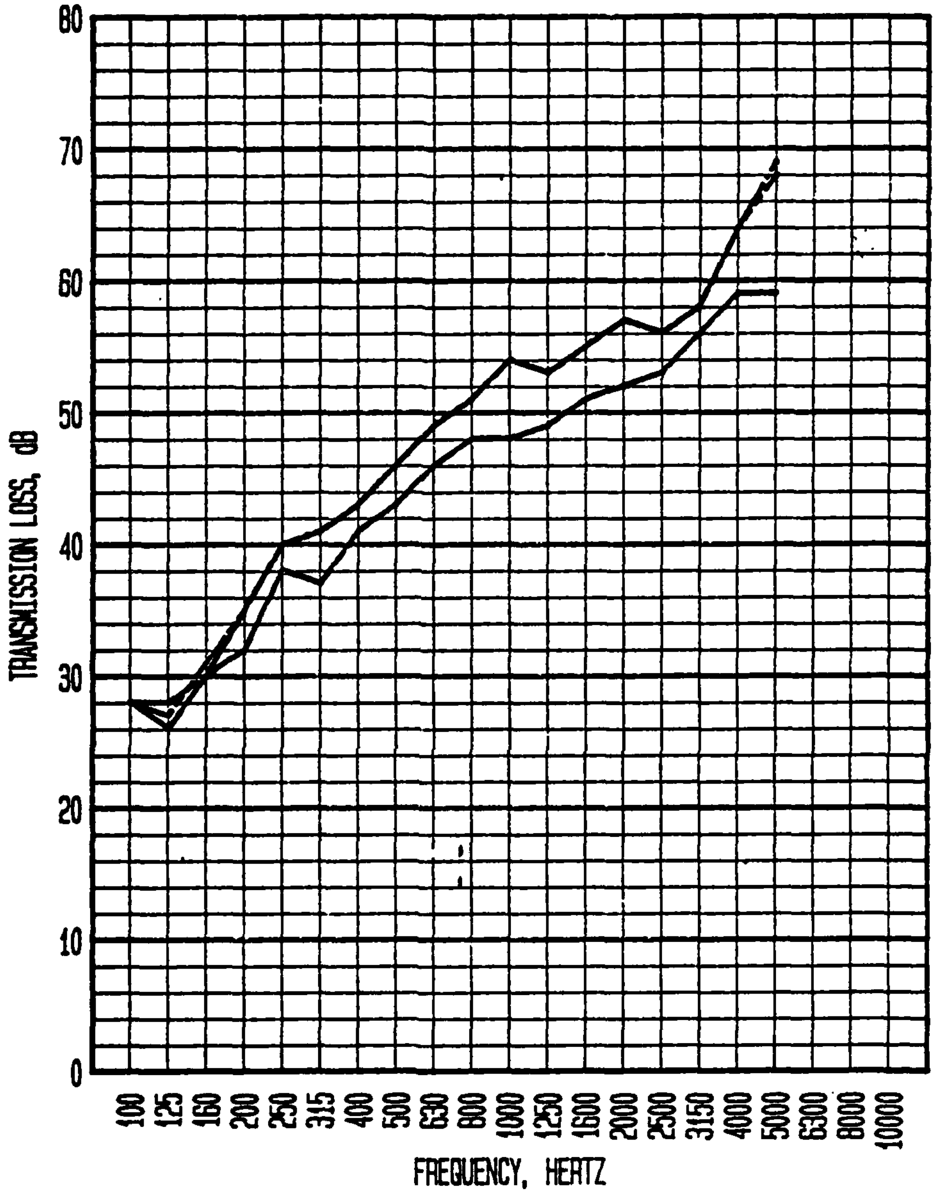


FIGURE 5. TRANSMISSION LOSS, WALL "B", WITH WINDOW BLOCKED

————————	CRAWL SPACE VENTED	STC=46
———·———	CRAWL SPACE ACOUSTICALLY TREATED	STC=49
—·—·—·—·—	CRAWL SPACE VENT BLOCKED	STC=49

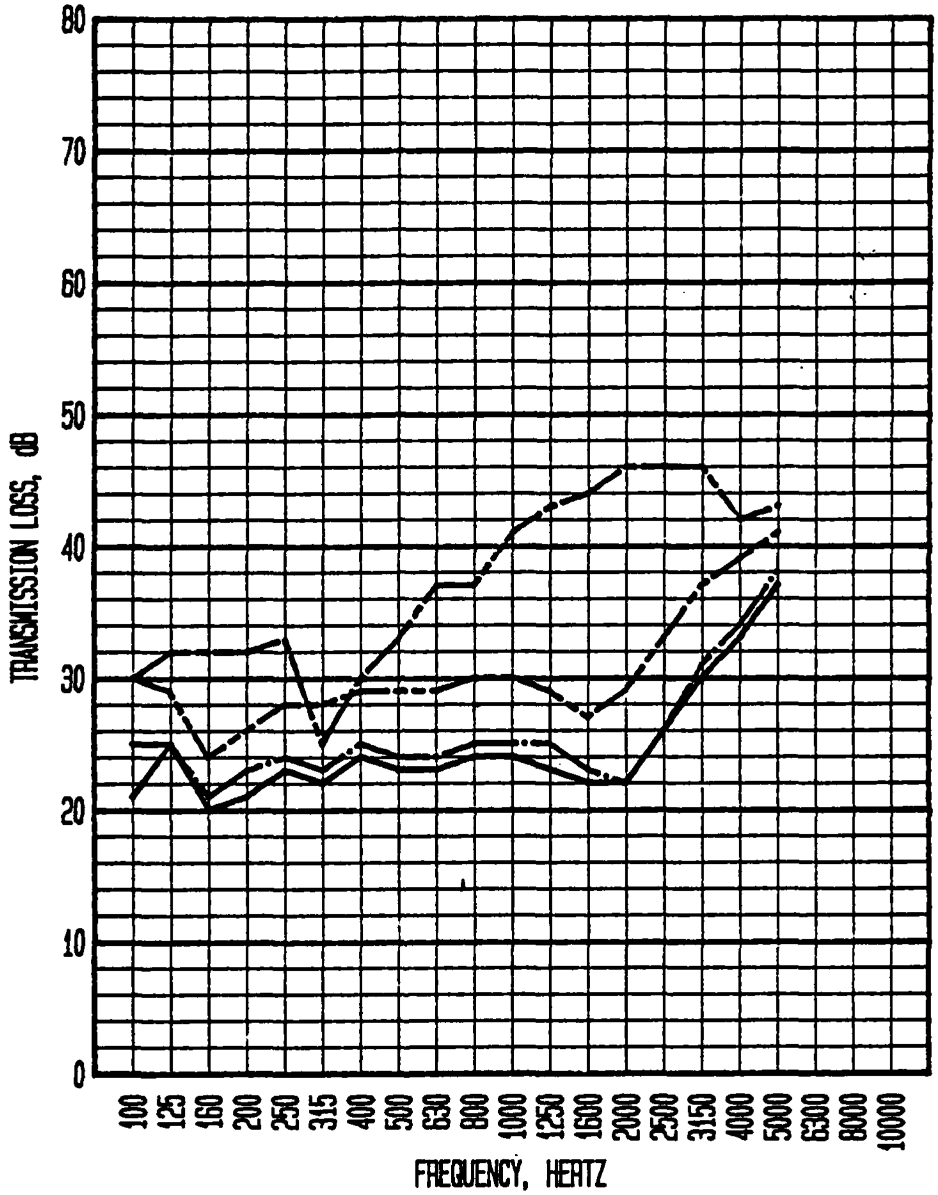


FIGURE 6. TRANSMISSION LOSS, WALL "C"

————	STEEL SASH WINDOW (UNLOCKED)	STC=24
——·——	STEEL SASH WINDOW (LOCKED)	STC=25
——-—-—	WINDOW AND WALL SEALED	STC=30
——-·-——	REPLACEMENT WINDOW	STC=37

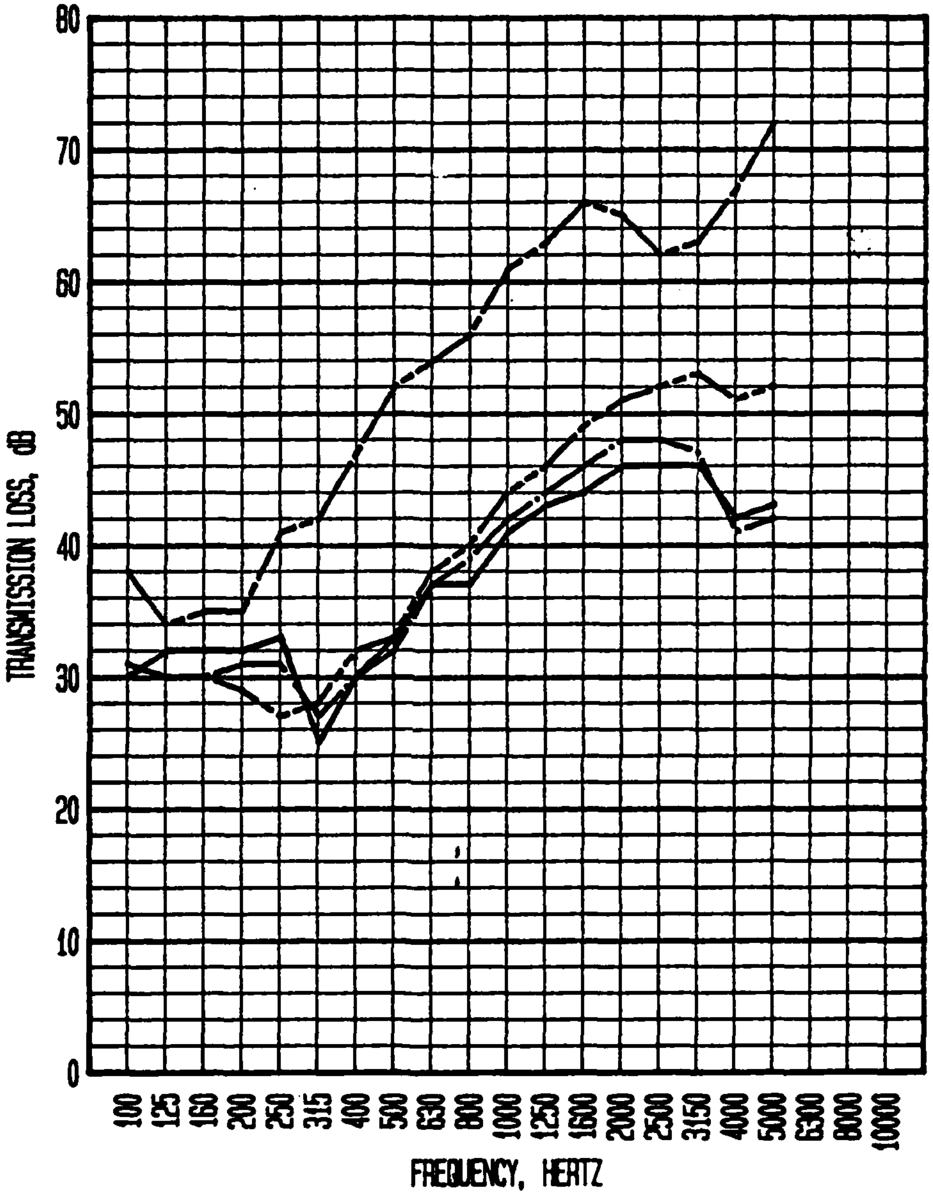


FIGURE 7. TRANSMISSION LOSS, WALL "C"

————	REPLACEMENT WINDOW (DOUBLE GLAZED)	STC=37
——·——	FURRED AND INSULATED EXTERIOR OF WALL	STC=39
—-—-—--	ADD STORM WINDOW (TRIPLE GLAZING)	STC=39
——-——-	FURRED WALL PLUS WINDOW BLOCKED	STC=52

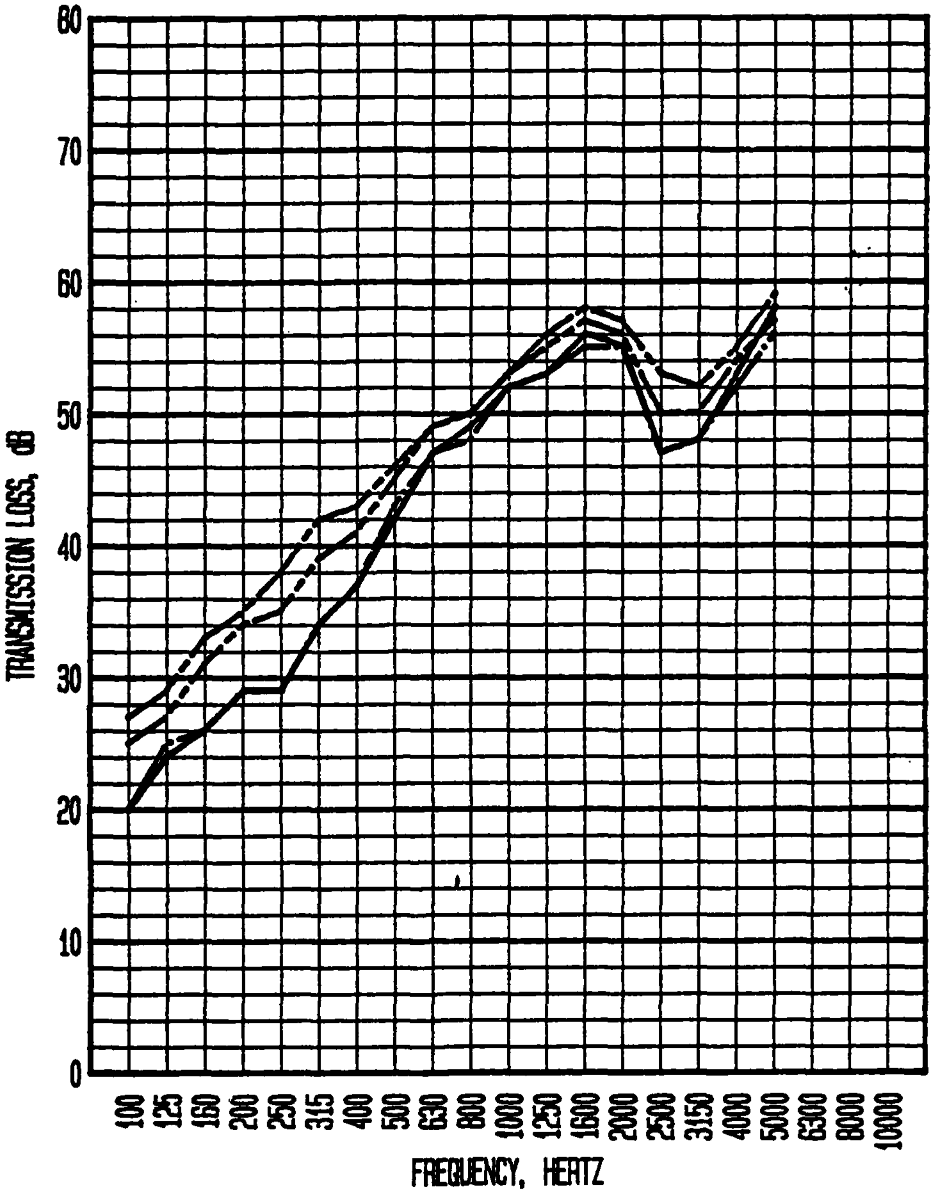


FIGURE 8. TRANSMISSION LOSS, ROOF/CEILING 'D'

————————	ORIGINAL CONSTRUCTION	STC=43
——·——	ROOF VENT BLOCKED	STC=43
— — — —	EXTRA ATTIC INSULATION	STC=47
—·—·—	EXTRA INSULATION PLUS EAVE VENT BLOCKED	STC=49

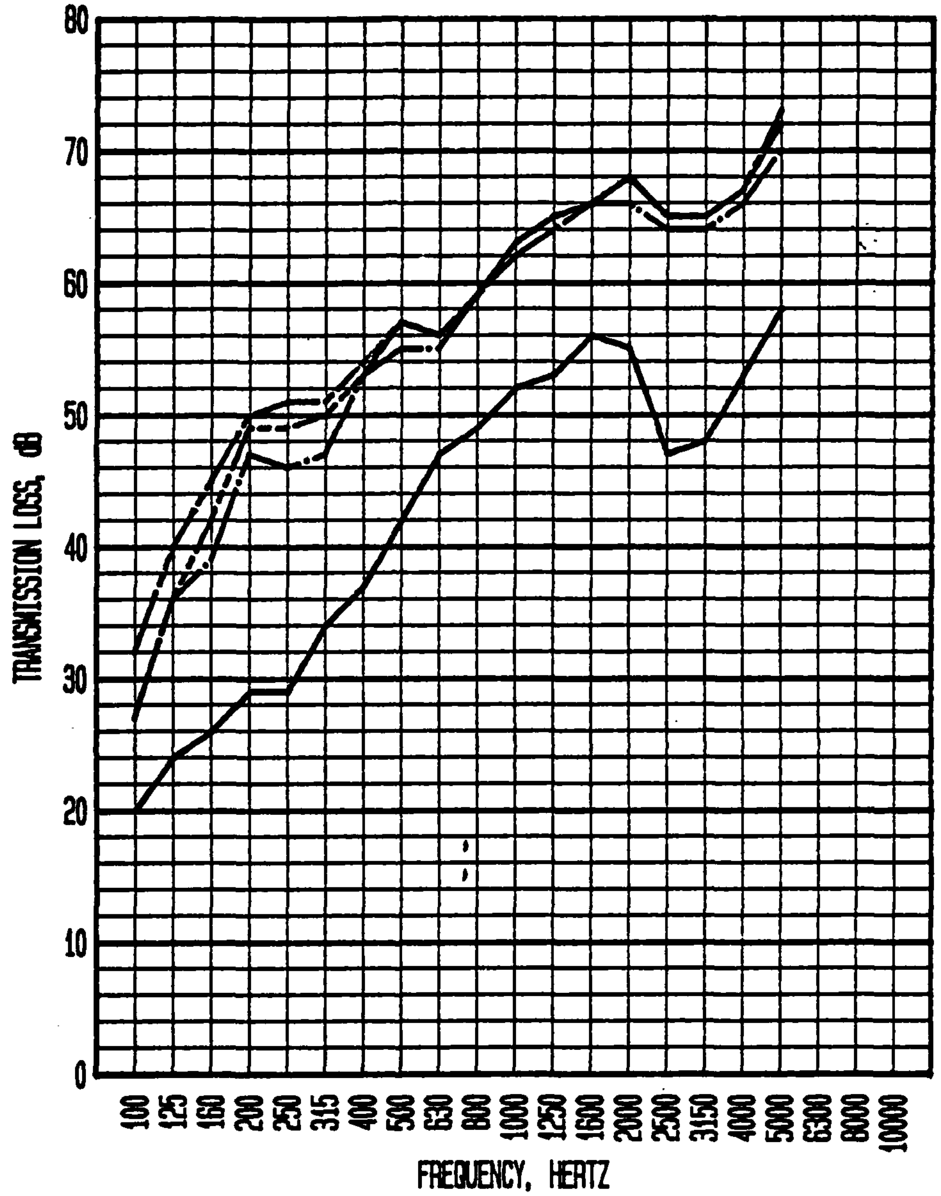


FIGURE 9. TRANSMISSION LOSS, ROOF/CEILING 'D'

————	ORIGINAL CONSTRUCTION	STC=43
——·——	SUSPENDED CEILING, IMPROVED SCUTTLE WITH OPEN CELL TAPE	STC=57
—-—--	SUSPENDED CEILING, IMPROVED SCUTTLE WITH CLOSED CELL TAPE	STC=59
——-——-	SUSPENDED CEILING, IMPROVED SCUTTLE AND ADDED ATTIC INSUL.	STC=60

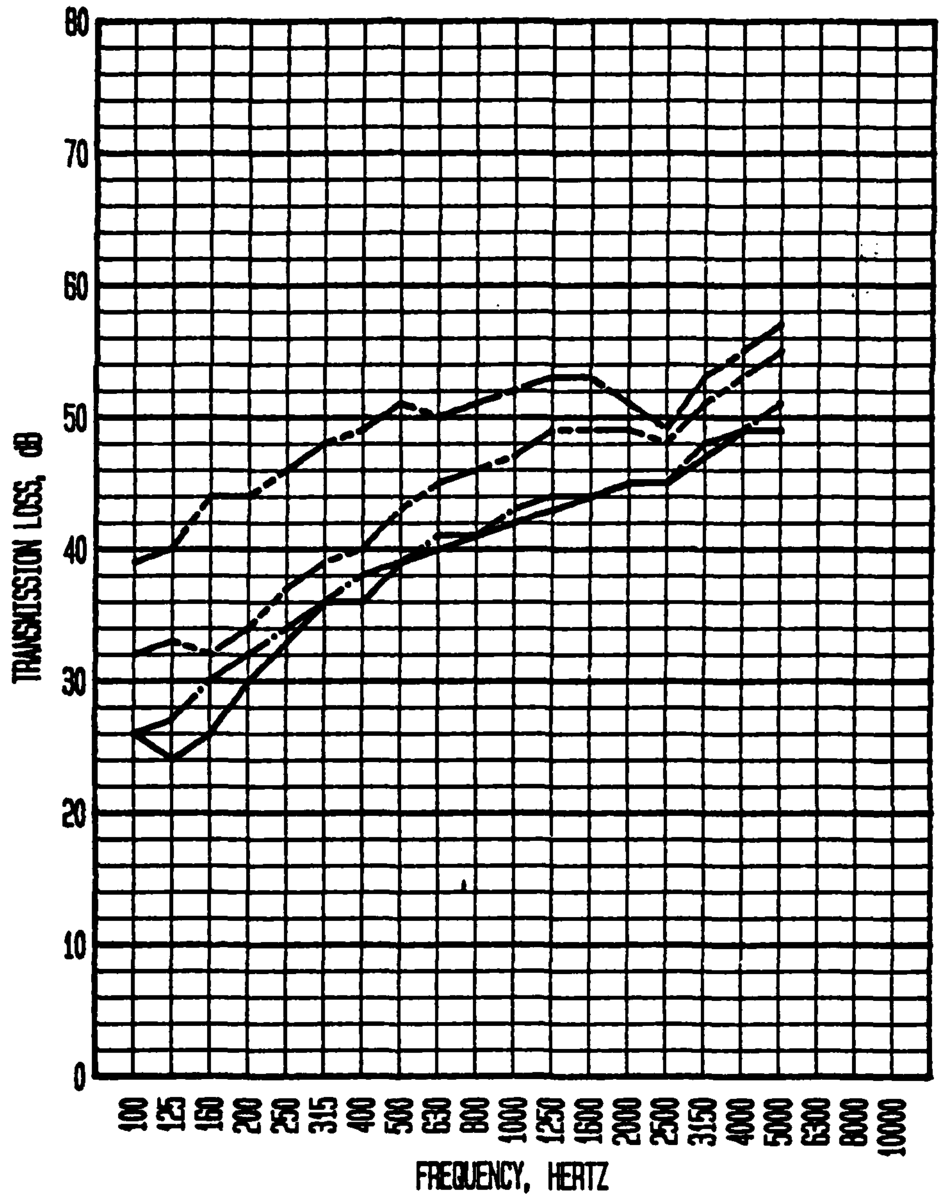


FIGURE 10. TRANSMISSION LOSS, ROOF/CEILING 'E'

————	ORIGINAL CONSTRUCTION	STC=41
——·——	SOUND ABSORPTION ADDED TO BEAM CLOSURE	STC=42
— - — - -	INTERIOR AND EXTERIOR CAULKED	STC=46
—— — ——-	SUSPENDED CEILING AND ADDED INSULATION	STC=51

Comments on Test Panel "A" Results - As was discussed above, small changes in the STC rating of a partition would pass as unnoticed. While wall "A" starts the best acoustically of the three initial or base wall structures, an STC rating of 32 is considered hardly better than "poor". With a complete job of caulking, the STC is improved 3 dB. This change would be noticeable acoustically but only barely so. Adding a 1/4 inch thick storm window or adding an insulated furred wall added another 3 dB. However adding a 1/4 inch thick storm window and adding an insulated furred wall improved the sound transmission performance of the wall 12 dB. This is a major improvement that would be considered significant by the residents. The overall improvement at this point of 15 dB would be judged very significant, and would change the overall sound transmission from "poor" to "good".

The improvement of 3 dB of two retrofits considered individually or 12 dB improvement considered together illustrates an important principle of sound transmission control. In order to improve the rating by 3 dB it is necessary to reduce the transmitted sound power by a factor of two. Evidently the amount of sound power transferred through the single glazed window and through the minimum insulated wall were about equal (taking into account the relative areas concerned). Either retrofit reduced the amount of sound power transmitted through that area by a factor of perhaps fifteen or more. This had the effect of reducing the overall sound power transmitted by a factor of two, since one of the two approximately equal modes of transmission was effectively eliminated. When both paths are reduced by a factor of fifteen, the overall power transmission is also reduced by a factor of fifteen and the true value of both retrofits can be realized.

The effectiveness of the 1/4 inch thick storm window in reducing sound transmission can be seen in the last test. By completely blocking the window opening acoustically, no further improvement in STC was noted.

By noting Figure 2, it is observed that the improvement in transmission loss by adding a 1/4 inch interior stormglazing and/or furring the interior wall 1-1/2 inch is not uniform as a function of frequency. With either retrofit, the increase in transmission loss is minimal for frequencies at and below 500 Hertz. In combination, a significant increase in transmission loss is achieved except at the very lowest frequencies.

The air leakage test results of wall "A" were very similar for both positive and negative pressurization. Caulking the interior of the window frame alone produced minimal reduction in the air leakage rate. Caulking the baseboard had a greater reduction. But the two in combination showed even more improvement illustrating a synergistic effect, that was also observed in other parts of this investigation. Comparing the air leakage results shown on test No. 4 with No. 5, which represents two different paths of reaching the same end condition, show good reproducibility of the testing procedures and construction techniques utilized.

Caulking the exterior of the wall produced a minor further reduction in air leakage rate, after the interior had been completely sealed. It is the opinion of the investigators that similar results would have been obtained had the exterior of the wall been sealed first, i.e., completely sealing the exterior initially would have produced the major reduction, with further caulking on the interior adding only a minor improvement. Therefore, establishment of an air barrier can be accomplished effectively by completely sealing either the exterior or the interior surface of the wall. Sealing both the exterior and interior surfaces would not be justified. The choice between whether the exterior or the interior surface should be sealed depends on other factors such as cost, expected life, and accessibility of all joints for accomplishing a complete seal.

Sealing of the electrical receptacles, both gasketing the cover plate and plugging the outlets, reduced the air leakage rate about 4.7 cfm for the two duplex receptacles. While not particularly significant by itself, when multiplied by the total number of outlets and switches located in outside wall of a typical residence, the associated leakage does indeed, become appreciable.

The thermal resistance of the basic wall "A" construction was 7.0 hr.sq.ft.^{o}F/Btu. When retrofit "A3" was added, which consisted of 1-1/2 inch steel Zee furring installed horizontally with R-5 mineral fiber insulation between the furring, the thermal performance of the wall increased to 12.4, an increase of 5.4. The improvement in thermal performance, above that expected, was caused by installation of the furring crosswise to the studs. This

minimized the short circuiting effect of the studs in the original wall "A" construction.

Should added insulation be economically justified, above that afforded by R-5 mineral fiber insulation, alternative constructions to be considered would include extruded foamed polystyrene board (R-8 at 1-1/2 inch thickness) or foil faced foamed polyurethane board (R-12 at 1-1/2 inch thickness). Both materials are flamable and require special considerations for fire protection, such as facing all exposed surfaces with 1/2 inch gypsum board. The thermal resistances quoted are for typical winter conditions.

Comments on Test Panel "B" Results - The acoustical test results of wall "B", with the window open, emphasizes the futility of attempting any measure of sound control if the windows must be opened for ventilation and/or cooling. One alternative is installation of air conditioning so that comfort may be maintained with the windows closed. Where cooling or dehumidification is not a requirement, ventilation may be provided by forced draft. In this the associated ducting must be treated acoustically to prevent both fan and exterior noise from being transmitted into the interior.

Unfortunately, the original single glazed aluminum horizontal slider type window installed in wall "B" was not of a design that would be considered typical of Navy construction (one of the hazards of dealing with a building material dealer instead of directly with the manufacturer). The air leakage rate of the original window was significantly different depending on whether the interior was pressurized or depressurized. This was caused by positive air pressure deflecting the fixed sash away from the supporting external frame, and thereby opening up additional leakage area. Adjusting the fixed sash greatly reduced the leakage. Note also that the air leakage performance of this sash was much poorer in the locked position than when simply closed. This was caused by defective design or assembly which caused the closure between the fixed and movable sashes to be forced apart by the act of latching or locking the movable sash.

Replacing the horizontal slide sash with one typical of Navy Family Housing resulted in a large reduction in the air leakage rate and a minor imporvement in the sound

transmission properties. Caulking the window frame to the wall produced a negligible improvement in the air leakage rate. However, this sash unit still suffered to lesser degree the problem of the unit originally installed: the operation of latching in part reduced air leakage area but also caused frame distortion which increased leakage in another area. Net result: little or no net improvement in air leakage from locking the sash. However readjusting the latching mechanism did produce a marked improvement.

The second retrofit, adding a commercially available aluminum storm window unit to the exterior of the prime unit, produced a marked improvement in the sound transmission class (8 STC units), but did little to reduce air leakage. Note however in Figure 4 that all of the improvement was at frequencies above 250 Hertz. At low frequencies the storm window provided little improvement.

Both the prime window and the storm window were provided with water drains in the bottom horizontal frame members. While these drains may be effective in preventing rain water from entering, they also do little to reduce air leakage.

As a side experiment all of the drains in the prime window were caulked and obvious leaks in the sash to frame joints were taped. While not a practical retrofit, this produced a marked improvement in the air leakage rate. It also produced a very large improvement in the sound attenuation (in fact, 1 dB greater than adding a storm window (refer to Figure 4). When the window was acoustically blocked and sealed, there was a further large improvement in the sound transmission properties (refer to Figure 4).

The third retrofit of wall "B" involved acoustically treating the crawl space. This portion of the investigation was conducted with the window blocked, since both the air leakage and the acoustic performance of the wall with the window active was so poor as to mask any effects of the crawl space treatment.

Acoustical treatment of the crawl space consisted of installing an acoustical baffle to the crawl space vent and sound absorbing material to the underside of the floor (which would also reduce heat loss through the floor). This installation involved removing and replacing the sub-flooring (since the crawl space was not of sufficient

height to accomplish this from the bottom as would normally be the case). The air leakage rate after reinstallation of the floor was only 1 cfm different than before, indicating good reproducibility of the construction and testing procedures. Taping the joints in the subfloor reduced the air leakage to nearly zero. It should be emphasized the stucco exterior surface was new. It had no significant shrinkage or settling cracks; thus the only air leakage path outside of the window unit itself was the window frame to wall joint and through the crawl space. In actual field construction, with aging the stucco is frequently cracked, which would offer additional leakage paths.

The sound transmission with the crawl space vent blocked was identical to that with the crawl space acoustically treated. This indicates that the treatment was completely effective. However, the high level of overall STC values with the window blocked, compared with that with the storm window added to the prime window, means that acoustical treatment of the crawl space would not result in a noticeable overall improvement until additional acoustical treatment was afforded the window.

Comments on Test Panel "C" Results - Normally wall "C", being constructed of a massive material such as concrete masonry units, would have been expected to perform well acoustically. However the excessive leakage of the steel casement sash window unit was the cause of very poor overall performance, both for air leakage and sound transmission. Note that when unlocked, air leakage with the interior under positive differential pressure was substantially more than with negative pressure due to the air pressure tending to open the sashes. This was true both when the sash units were gasketed and when not gasketed. When the sashes were gasketed and locked the overall air leakage rate was greatly reduced and approximately equal under positive and negative pressure differentials. Adding gasketing to the sash is a low-cost effective measure for both control of air leakage and improvement of sound transmission.

A number of other areas of sealing to reduce air leakage were investigated. Since the basic construction was slab-on-grade with concrete masonry unit walls, it was assumed that the wiring for electrical service would be from the attic space, or top of the wall. Sealing these wiring holes was effective as an air leakage control

measure, but usually not a practical retrofit due to lack of accessibility. An alternative studied was the sealing of the interior skin of the wall, including: baseboard, electrical outlets, and window frame. These measures had effectiveness comparable to sealing the wiring holes. Sealing the wire holes and sealing the interior skin in combination provided a minor improvement over doing either retrofit alone.

The second retrofit, C2, consisted of removing the original single glazed steel casement sash and replacing it with a double-glazed thermal-break single-hung aluminum window unit. This unit was specifically designed for retrofit applications. The replacement was a relatively simple operation. As a result, the overall air leakage was reduced to practically zero. The sound transmission was improved 7 STC units over the best obtainable with the original steel sash window when it was thoroughly sealed and 12 STC points better than the original construction with the steel sash window locked.

The third retrofit, C3, consisted of furring out the exterior of the wall, adding 1-1/2 inches of rigid foam polystyrene board and restuccoing the exterior. This was primarily a thermal conductance improvement retrofit, however it did improve the overall sound transmission class 2 dB. This indicates that prior to the retrofit both the wall and the window contributed appreciably to the sound transmitted, with the window portion the larger of the two.

Adding an interior storm window to the double glazed prime window, to make the combination a triple glazed unit, effected no change in the overall Sound Transmission Class single number rating.

While the ear heard a distinct improvement by the addition of the storm window, all of the reduction was at the high frequency end of the spectrum. The low frequency portion, which in this case was critical in the STC calculation, was not materially affected. (Actually, the sound transmission loss was poorer at 200 and 250 Hertz, see Figure 7.)

A part of the problem is believed due to the method of attachment of the storm to the prime window. While the design tested was simple, it provided little acoustical isolation. Addition of a storm window, of the type tested,

would be helpful in improving conditions where aircraft generated landing noise predominates since the high frequencies dominate on landing. It would be totally ineffective in improving conditions caused by take off generated aircraft noise.

When the window opening of the retrofitted wall was acoustically blocked the STC rating was improved an additional 13 units, compared with 2 units improvement when retrofit "C3" was added. This indicates that the full potential of "C3" (furred exterior wall) for acoustical improvement can not be realized without additional corrective measures being taken at the window area.

Comments on Test Panel "D" Results - Roof/ceiling construction "D" consisted of a pitched roof on trusses with a gypsum board ceiling surface. The air leakage rate was greater with positive interior pressure differential than with negative pressure, due to the lifting of the scuttle panel. Removing effects of the scuttle (by replacing it with solid gypsum board) reduced the air leakage rate 20-30 cfm. By installing a lens in the single recessed ceiling light fixture installed, the air leakage rate was reduced about 40 cfm. These two measures in combination practically eliminated air leakage through the roof/ceiling assembly, but did little to improve the sound transmission properties.

It was thought that adding an acoustic baffle sound trap to the roof vent would improve sound isolation (retrofit "D2"). Initially the roof vent was completely blocked acoustically. This resulted in no change in the overall STC rating, so retrofit "D2" was not explored further.

Retrofit "D1" consisted of adding blown mineral fiber insulation to the attic space, increasing the R value by an average of 12 units to a total of R19. This added 4 STC units to the overall Sound Transmission Class single number rating. However there was little reduction in the "coincidence dip" at 2500 - 4000 Hertz (see Figure 8). Blocking the eave vent strip produced an additional 2 dB in the overall STC rating, however this would not be a practical retrofit, particularly in cold climates where this procedure would increase the possibility of moisture condensation problems in the attic. It is interesting to note that the combination of added attic insulation and blocked eave vent provided a substantial improvement in

the low frequency sound transmission, below 500 Hertz (see Figure 8).

Retrofit "D4" consisting of installing a dropped insulated ceiling with an improved design attic access scuttle. The improvements in the scuttle consisted of gasketed joints, a hinged door and positive latching. The overall STC rating was increased 13 dB from that of the original roof/ceiling construction. Replacing the open cell foam tape used as a gasket with closed cell foam tape reduced air leakage 13 CFM and increased STC 1 dB. The amount of reduction in air leakage was unexpected as the expected leakage due to porosity of the open cell foam did not appear visually to be that large. Adding insulation to the attic space, increasing the R value to 19, provided an additional 1 dB to the roof/ceiling assembly with the suspended ceiling (see Figure 9).

Comments on Test Panel "E" Results - Roof/ceiling construction "E" consisted of an exposed deck on exposed beams, with a low slope build-up roof over 1 inch of woodfiber insulation on top of the deck.

The original construction had an overall STC rating of 41. Adding sound absorbing material to the closure space, between the beams, provided a small but insignificant improvement in the sound transmission.

The rocf/ceiling "E", with the open construction details cf the exposed beam and the closure between, provided many opportunities for air leakage. Caulking of these points provided a marked reduction in air leakage and a 4 dB improvement in STC rating. As with other caulking retrofits investigated, the sealing could be effectively accomplished on either the exterior or the interior surface. Sealing the interior, after the exterior had been caulked, accomplished little further reduction in the air leakage rate. Note in Figure 10, that the improvement in sound transmission loss due to caulking was over the whole frequency range. Substantial improvement was achieved at low frequencies in addition to the mid-range and high frequencies.

Adding an insulated suspended ceiling, between the exposed beams, provided a further substantial improvement in the STC rating of 5 dB. Again note in Figure 10 that significant further reductions in sound transmission were achieved in low and mid-range frequencies.

Addition of the insulated suspended ceiling also provided a major reduction in the thermal conductance of the roof/ceiling assembly. As shown in Table IV the thermal conductance of the assembly (C-value without consideration of surface air film coefficients) was reduced from 0.18 to 0.05 Btu/hr.sq.ft.°F, a factor of 3.5 times. While the thermal resistance of the added insulation was 19, the overall thermal resistance of the assembly was increased only 14 units due to the "thermal shorting" effect of the exposed beams. In this case the ultimate in thermal performance improvement was slightly sacrificed in order to maintain the desired aesthetic effect of the exposed beams.

It should be pointed out that the STC rating of both of the original construction roof/ceiling assemblies, "D" and "E", was substantially higher than that of the original wall assemblies. The sound level observed in a given room from outside noise sources is a combination of the sound transmitted through the walls and that through the roof/ceiling. In the case of lower level rooms of a multi-story building, the interior sound level due to outside noise sources is solely that transmitted through the walls. Thus to achieve a reduction in interior sound level, first attention generally should be directed toward improving the STC of the wall assembly rather than the roof/ceiling.

Analysis of Data

The technical data developed during the course of this investigation is directly useful to a professional acoustician, or an energy conservation engineer. However, as presented in the previous sections, the format is not helpful to a Navy base facilities management person. While he is skilled in the general aspects of building construction and maintenance, he can not be expected to be able to utilize directly technical data on acoustics, air leakage and insulation.

Appendix J was written with the base facilities engineer in mind. The purpose of that section is to provide him with a general understanding of acoustical retrofit measures, as

applied to control of exterior noise in family housing units.

The purpose of this section is to reduce the technical data of this to general terms. Hopefully, between the two sections, the facilities management person can decide whether a particular retrofit has sufficient potential merit from the expected benefits to justify the expenditure.

Once a decision has been made on a general basis, a professional engineer can develop the details of the retrofit. This detailed analysis would include consideration of the present condition and problem areas of the specific buildings to be improved, orientation and proximity to aircraft operations (and other excessive noise sources), local construction labor practices and wage rates, local weather conditions including average winter and summer temperatures, and humidity, heating degree days and summer cooling hours. With this detailed local condition and cost analysis a benefit-to-cost analysis can then be prepared.

General Performance Analysis - In order to reduce the technical data developed to a general basis, a number of assumptions were made. These will be detailed.

The acoustical and air leakage data was developed on test specimens of nominal 8 by 14 feet or 112 square feet. In the case of walls, a 3 by 4 foot window was included in the construction. All of the cost and performance data have normalized to a basis of 100 square feet building envelope area. This means that a typical wall section as tabulated in the cost/performance summary will contain 12 x 100/112 or 10.7 square feet of window area and 100 x 100/112 or 89.3 square feet of opaque wall area.

Cost data for the various retrofits were estimated on the basis of costs for various tasks tabulated in "Repair and Remodeling Cost Data - 1982"[15] and "1982 Means Cost Data"[16], both by R. S. Means Co., Inc. Labor costs used in the analysis have been tabulated in Table V. These include the various mark-ups for Workman's Compensation insurance, unemployment insurance, social security, and subcontractor overhead and profit.

In Table VI the installed cost of the elements of the various retrofits has been estimated. Material requirements were estimated and costs taken from "Repair and Remodeling Cost Data - 1982". These were marked up 10 percent at the subcontractor level. Subcontractor labor and material prices were marked up an additional 10 percent as would be the practice of the general contractor, to allow for his overhead and profit. No allowance has been made for costs of design and supervision, and for contingencies and extras.

TABLE V - AVERAGE NATIONAL CONSTRUCTION HOURLY LABOR RATES
JANUARY 1, 1982

Trade	Basic Rate Incl. Fringe	Subs Total Overhead and Profit	Total Subcontractor Rate
Bricklayer	17.60	9.00	26.60
Carpenter	17.00	9.05	26.05
Common Labor	13.55	7.20	20.75
Plasterer	16.50	8.35	24.85
Sheet Metal Worker	18.80	9.40	28.20
U. S. Average (skilled trades)	17.25	9.15	26.40
U. S. Average (helper)	13.35	7.05	20.40

Source: "Repair and Remodeling Cost Data - 1982" - R. S. Means Co., Inc.(15)

TABLE VI - INSTALLED UNIT COSTS USED IN ESTIMATING RETROFITS

Item	Cost	Unit
Acrylic latex caulk, 1/4" x 1/2"	$110	100LF
Ureathane foam sealant, 3/8" x 3/4" (aerosol handy pack)	188	100LF
1-1/2" metal zee interior wall furring, 24" OC	82	100SF
2 x 2 treated wood exterior furring, 24" OC (on masonry walls)	56	100SF
2 x 2 wood interior furring, 24" OC (on wood walls)	41	100SF
2 x 4 suspended ceiling joists, 24" OC (including headers)	64	100SF
2 x 6 suspended ceiling joists, 24" OC (including headers)	83	100SF
1 x 2 wood trim	88	100LF
Remove and reinstall existing trim	134	100LF
1-1/2" (R5) mineral fiber insulation, batt	27	100SF
3" (R11) mineral fiber insulation, batt	34	100SF
6" (R19) mineral fiber insulation, batt	46	100SF
6" (R13) mineral fiber insulation, blown-in	53	100SF
1-1/2" (R6) polystyrene, molded bead board	51	100SF
1-1/2" (R10) polyurethane board	104	100SF
4 mil polyethylene film vapor barrier	8	100SF
1/2" gypsum wall board, taped and finished	67	100SF
1/2" gypsum ceiling board, taped & finished	76	100SF
2" gypsum wallboard & polyurethane foam bd. composite (R10) taped and finished	134	100SF
Finish gypsum board corners (additional)	46	100SF
3/4" - 2 coat cement plaster stucco on masonry (including mesh)	168	100SF
3' x 4' exterior horizontal slider storm window, d.s. glazing	59	Unit
3' x 4' interior fixed storm window, 1/4" glazing	93	Unit
Remove steel sash window	22	Unit
3' x 4' single hung aluminum replacement window, double glazed, thermal break	203	Unit

Source: "Repair and Remodeling Cost Data - 1982"(15), "Building Construction Cost Data - 1982"(16), R. S. Means Co., Inc.

Assumptions made in Table VI:

Labor costs - national average for various trades, January 1, 1982 (Table V)

Material Costs - national average delivered to site, January 1, 1982, plus 10 percent markup

General Contractor Overhead and Profit - 10 percent added to subcontractor price including O&P

Contingencies and Extras - no allowance included

Design and Supervision - no allowance included

Location - no local adjustment made

Project size - greater than $5,000

Redecoration - cost not included in retrofit

The estimated thermal performance of a particular building section consists of two factors: air leakage and thermal conductance. The leakage of conditioned air through the building envelope is a result of infiltration and exfiltration of air under the influence of a pressure differential. The thermal conductance of heat through a building envelope section is the result of a temperature difference across that section. In the summer time, leakage of conditioned air through the building enevelope can result in double energy loss; loss of cooled air (sensible load) and loss of dehumidified air (latent load).

For simplification, it was decided to use 5000 heating degree (F) days as the basis for determining thermal performance effectiveness. 5000 degree days is a typical heating season for such locations as New York, New York; Philadelphia, Pennsylvania; Columbus, Ohio; St. Louis, Missouri; Topeka, Kansas; Pueblo, Colorado, and Seattle/Tacoma, Washington. For locations south of these points, the heating load would be less, but generally the added air conditioning load would more than make up the difference. For locations north of these points the heating load could be substantially higher (Minneapolis, Minnesota, with a typical heating season of 8400 degree days, could expect approximately 1.7 times the improvement in thermal performance cited).

The air leakage rate was determined for each of the constructions at ten points: 5 positive and 5 negative differential pressures. These were analyzed and the exponent for the relationship, flow = $(K \cdot \text{pressure})^n$ determined. If the leakage were all viscous flow, the exponent would be expected to be 1.0. If on the other hand, the leakage was all turbulent flow, the exponent would be 0.5. Other investigators have found typical air leakage exponents for houses to be in the range of 0.60 to 0.80. The range of exponents for tests conducted in this investigation was 0.68 and 0.81, with an average of 0.73.

Estimation of annual heat loss, due to air leakage, is a result of many factors. The two external or forcing factors causing the differential pressure are inside/ outside temperature differential and wind. The greater the difference in temperature between the inside and the outside of the building, the greater the pressure differential caused by the temperature or stack effect. Wind blowing on the external surface of a building causes a negative internal pressure differential on the windward side (infiltration), and a positive internal pressure on the leeward side (exfiltration). At a wind speed of 25 mph, the differential pressure developed is 0.3 inches of water. This is also the test pressure differential required by the ASTM-E283 air leakage standard test method.

Since both temperature difference, and wind velocity (speed and direction) are constantly varying during the heating season, the question of how to convert air leakage data at specific pressure differentials to a seasonal average for a particular building, does not have a unique answer. Complicating the issue are site factors such as the external terrain and local shielding, and leakage site distribution (between ceiling, wall and floor).

D. T. Grimsrud and associates at the Lawrence Berkeley Laboratory have proposed a method for estimating annual heat loss due to air leakage.(18) A series of air flow measurements are made on a building or building element at various pressure differentials, using a fan. These data are plotted on a log-log graph, and the line (usually straight) extrapolated to 4PA (0.016 inch water) pressure difference. From this the equivalent leakage area can be estimated. On the basis of typical weather data Grimsrud et al have estimated the seasonal average temperature difference and average wind velocity for various location.

To these they apply correction factors for terrain and local shielding effects, and leakage site distribution. With all these factors taken into account, plus the average degree hours per heating season for a particular location, they are able to estimate the seasonal heat loss expected as a function of leakage area, which was determined as above.

A simpler approach to determine the average seasonal air leakage, is to divide the leakage rate, as determined by fan pressurization/depressurization at a particular pressure differential by a constant. Various constants have been suggested, ranging from 4 at 4 PA (0.016 inches water) to 20 at 0.2 inches water. This was the approach taken in this investigation. The average value of the exponent in the volume/differential pressure logarithmic equation was found to be 0.73. Using this value, the constant of 20 at 0.2 inches water extrapolates to a constant of 27 at 0.3 inches water differential pressure. The constant of 27 is generally consistent with the other constants, when extrapolated. It was also checked against the Grimsrud suggested procedure for a number of locations, and gave heat loss data in general agreement.

The air leakage data in Table III (CFM at 0.3 inches water ΔP) was converted to seasonal average air leakage rate by dividing by 27 as above. The seasonal average air leakage rate was used to determine the heat loss due to infiltration per 100 square foot area and assuming 5000 degree days in the heating season (see Table VII).

The heat loss due to thermal conductance was calculated on the basis of procedures and data in the 1981 ASHRAE Handbook of Fundamentals, Chapter 23.[9] In the case of wall construction "A", the thermal conductance was both calculated and measured using the Guarded Hot Box, according to ASTM-C236.[13] The comparison of the results of the two methods, shown in Table VIII, is total agreement. This must be considered in part fortuitous, however it does lend credence to the ASHRAE calculation procedures used to evaluate heat loss through the other structures.

TABLE VII - ASSUMPTIONS USED IN ESTIMATING ANNUAL HEAT LOSS

Air Leakage

- slope of leakage curve = 0.73 (flow = $(\Delta P)^{0.73}$)
- seasonal leakage conversion factor of 27 (at 0.3 In. H_2O ΔP)
- standard air density of 0.075 lb./cu. ft.
- 5000 degree (F) days per heating season
- 100 sq. ft. building envelope surface area (wall or ceiling)

Thermal Conductance

- ASHRAE calculated overall thermal transmittance or U-factor (except for four guarded hot box tests)
- 5000 degree (F) days per heating season
- 100 sq. ft. building envelope surface area (wall or ceiling)

TABLE VIII - COMPARISON OF CALCULATED AND MEASURED THERMAL CONDUCTANCE ("U-VALUE") - WALL "A"

Element	Thermal Resistance hr.SF °F/Btu Panel Area	Framing Area
Outside surface	0.17	0.17
5/8" plywood siding	0.77	0.77
R5 insulation	5.00	
2" air space	1.02	
3 - 1/2" fir framing		4.38
1/2" gypsum board	0.45	0.45
Inside suface	0.68	0.68
Total resistance	8.09	6.45

16" OC wall framing (assume 20% framing factor)

$U_{calc} = 0.80 \times 1/8.09 + 0.20 \times 1/6.45 = 0.130$ Btu/hr SF °F

Procedure - Chapter 23 ASHRAE 1981 Handbook of Fundamentals(9)

$U_{measured}$ (GHB) = 0.130 Btu/hr SF °F (ASTM C236)

The estimated cost of the retrofit, the sound transmission (STC), and annual heat loss for the various constructions investigated are tabulated in the Performance Summary, Table IX.

TABLE IXa - PERFORMANCE SUMMARY - TEST WALL "A"
(Frame wall with plywood siding, on slab-on-grade foundation with fixed sash window)

Construction	(1) Estimated Installed Cost	STC	(2) Annual Heat Loss MBtu/Season Air Leakage	Thermal Con-ductance	Total
Base wall constr.	-	32	0.30	2.81	3.11
Caulk and seal interior of wall (elect. recept. labor n/i)	$71	35	0.03	2.81	2.84
Add 1/4" interior storm window to sealed wall	83	38	(E0.02)	2.04	2.06
Add 1-1/2" interior insulated (R5) furred wall to sealed wall (original window)	168	38	(E0.02)	2.22	2.24
Or add 1-1/2" interior composite insulated wall (R10) to sealed wall (original window)	133	-	(E0.02)	2.00	2.02
Add 1/4" storm and 1-1/2" (R5) furred wall	83 168	47	(E0.01)	1.47	1.48
Add 1/4" storm and 1-1/2" composite wall	83 133	-	(E0.01)	1.23	1.24

(1) Basis is 100 SF gross wall area
(2) Basis is 100 SF gross wall area, 5000 deg. day heating season
n/i - not included in cost estimate
E - Estimated value

TABLE IXb - PERFORMANCE SUMMARY - TEST WALL "B"
(Frame wall with stucco exterior on crawl space foundation with aluminum horizontal slider window)

Construction	(1) Estimated Installed Cost	STC	(2) Annual Heat Loss MBtu/Season Air Leakage	Thermal Conductance	Total
Wall with original window	-	28	0.27	2.69	2.96
Base wall construction	-	29	0.17	2.69	2.86
Caulk and seal wall	$71	30	0.12	2.69	2.81
Install exterior storm sash	53	38	0.10	1.92	2.02
Base wall with window blocked	-	46	0.03	2.06 (3)	2.09
Acoustical treat crawl space (sound trap & R11 acoustical insulation)	53	49	0.03	0.85 (3)	0.88

(1) Basis is 100 SF gross wall area.
(2) Basis is 100 SF gross wall area, 5000 deg. day heating season.
(3) Basis is 100 SF gross floor area.

TABLE IXc - PERFORMANCE SUMMARY - TEST WALL "C"
(Concrete masonry unit (block) wall with stucco exterior, foil faced gypsum board interior and steel casement sash window)

Construction	(1) Estimated Installed Cost	STC	(2) Annual Heat Loss MBtu/Season: Air Leakage	Thermal Con-ductance	Total
Base wall construction	-	24	0.65	3.80	4.45
Gasket and lock (n/c) sash	$15	30	0.16	3.80	3.96
Caulk and seal wall	71	30	0.07	3.80	3.87
Replace sash with single hung thermal break *double glazed* window unit	263	37	0.01	3.10	3.11
Add 1-1/2" exterior insulated (R6) wall restucco (original window)	275	-	(E0.07)	2.41	2.48
Add 1-1/2" exterior insulated wall and double glazed window	275 263	39	(E0.01)	1.73	1.74

(1) Basis is 100 SF gross wall area.
(2) Basis is 100 SF gross wall area, 5000 deg. day heating season.
E - Estimated value

TABLE IXd - PERFORMANCE SUMMARY - TEST ROOF/CEILING "D"
(Asphalt shingles on plywood deck on spaced trusses with gypsum board ceiling)

Construction	(1) Estimated Installed Cost	STC	(2) Annual Heat Loss MBtu/Season Air Leakage	Thermal Conductance	Total
Base roof/ceiling construction	-	43	0.32	1.29	1.61
Seal scuttle, add lens to recess light (n/i in cost)	$ 11	43	0.02	1.29	1.31
Block attic space roof vent	-	43	(E0.02)	1.29	1.31
Remove recess light (n/i in cost) add attic insulation from R7 to R19	53	47	(E0.02)	0.56	0.58
Install R11 insulated suspended ceiling (with improved scuttle and original attic insulation)	193 (74)	57	(E0.01)	0.57	0.58
Install insulated suspended ceiling and added attic insulation	193 74 53	58	0.01	0.36	0.37

(1) Basis is 100 SF gross ceiling area
(2) Basis is 100 SF gross ceiling area, 5000 deg. day heating season.
n/i - not included in cost estimate
E - Estimated value

TABLE IXe - PERFORMANCE SUMMARY - TEST ROOF/CEILING "E"
(Built-up roof on insulated exposed deck with exposed beams)

Construction	(1) Estimated Installed Cost	STC	(2) Annual Heat Loss MBtu/Season Air Leakage	Thermal Con-ductance	Total
Base roof/ceiling construction	-	41	0.15	1.80	1.95
Caulk and seal beams and closures	$ 189	46	0.00	1.80	1.80
Add suspended R19 insulated ceiling between exposed beams	253	51	(E0.0)	0.56	0.56

(1) Basis is 100 SF gross projected ceiling area.

(2) Basis is 100 SF gross projected ceiling area, 5000 deg. day heating season.

E - Estimated value

The U. S. Department of Energy compiled the average cost for the various commonly used heating fuels, for 1981 along with projections of costs to 1995 (1981 constant dollars). This was published in the Federal Register.[17] Costs of fuels commonly used for residential heating, along with expected seasonal heat plant efficiencies, are compiled in Table X. The unit is $/million Btu (MBtu).

TABLE X - U.S. AVERAGE HEATING ENERGY COSTS (RESIDENTIAL)

Fuel	Assumed Seasonal Efficiency	Total Full Cost (1981) dollars) per MBtu 1982 (Extrapolated)	1995 Projected
Fuel oil (distillate)	60%	$16.43	$27.08
Natural Gas	50%	9.63	14.90
Electricity (resistance)	100%	17.63	20.62

Source: DoE tabulation of fuel energy costs, 1981[17]

Dividing the cost of the retrofit by the annual dollar saving in heat loss gives the number of years required for simple payback. Considering only the energy saving benefit, and not attempting to place a monetary value on the reduction in sound transmission, many of the retrofits are in the range of five to ten years for simple payback with oil heat. With natural gas as a fuel the typical payback period, based on 1982 fuel costs, is even longer. Using an average fuel cost for natural gas over the period to 1995, the payback period based on energy saving is still generally unattractive as an investment.

A part of the problem of cost effectiveness is the general contractor labor rates used in the cost estimate (Table V). Generally caulking is regarded as a cost effective energy conservation measure. However, at a total cost of $110/100LF (Table VI), it is not too surprising that caulking is not attractive from a benefit-to-cost analysis. Of the $1.10/LF total estimated cost the breakdown is as follows:

$0.06/LF material cost (5.5%)
0.61 direct labor costs (55.5%)
0.33 subcontractor markup (29.9%)
0.10 general contractor markup (9.1%)
$1.10/LF Total

If the caulking is installed by the owner/occupant, so that the total cost is the $0.06/LF material cost, caulking becomes a very attractive energy conservation measure, with a simple payback period that is attractive, even with natural gas as a fuel. With the use of in-house crews for some of the retrofits rather than relying completely on outside contract labor, it is likely that the payback for more of the retrofits would also be financially attractive.

There is no known way the authors are aware of to place a dollar value on the benefits achieved through reduction of sound transmission. If through the addition of sound transmission control measures an otherwise uninhabitable dwelling unit can be made livable, the retrofit can probably be justified. However other investigators (2-6) have found the installation of effective sound control measures to be expensive. There is nothing developed by this investigation to indicate the contrary. To achieve a major reduction in the sound transmission properties, requires a major investment. However, significant and

noticeable improvements in acoustic performance can be made by at modest cost by sealing leaks and installing some form of double glazing. Generally windows were the weakest link in the overall acoustic performance of a wall structure. Initial attention in improving acoustic performance should therefore be directed toward the window. The single glazed window also contributed a significant portion of the overall thermal transmittance of the wall. Thus improvement of the window provides a meaningful dual benefit.

CONCLUSIONS

1. It was expected, and this investigation confirmed, that there were benefits to be gained in the form of increased sound isolation by taking retrofit measure aimed primarily at energy conservation (reduced air leakage and increased insulation level).

2. In family housing units, to improve acoustic isolation from exterior noise, the most important sound transmission path should be attacked first. Generally windows are the weak link acoustically in the building enevelope.

3. Retrofit measures which attack secondary noise leaks in the building envelope, will not provide noticeable improvement in the interior noise level.

4. The acoustical performance of the two roof/ceiling constructions tested was superior to that of the three wall constructions. Thus roof/ceiling constructions should not be retrofitted for acoustic purposes until after the wall performance has been improved.

5. Caulking and sealing of the exterior envelope can improve sound isolation and reduce air leakage.

6. If contract labor rates for installation of acrylic latex caulking, to be $1.10/linear foot for labor, material, and markup, the benefit-to-cost analysis makes the caulking retrofit of doubtful desirability; if installed by the owner at an estimated $0.06 linear

foot material only cost, the retrofit is very desirable.

7. Caulking and sealing of exterior walls can be accomplished by sealing either the exterior or interior surface; the choice of exterior or interior depends on accessibility and cost. Only a slight improvement was found when walls were completely sealed on both surfaces.

8. If windows must be opened for ventilation and/or cooling, no amount of sound isolation improvement to the wall or roof/ceiling will provide any overall reduction of the interior noise level in areas where the exterior noise level is high.

9. A commercial combination storm window, added to a prime window, improves sound isolation and reduces thermal conductance, may not reduce air leakage through the window assembly if drains for rain water are a part of the design.

10. Installation of an extra heavy storm window (1/4 inch thick glazing) provided a marked improvement in the acoustical performance of the window.

11. Replacing a single glazed steel casement style sash with an aluminum double-glazed thermal-break replacement type sash was very effective in reducing air leakage, sound transmission and thermal conductance.

12. Adding an insulated suspended ceiling provided a marked reduction in both sound transmission and thermal conductance.

13. Acoustically treating a crawl space area also provided improvement by greater sound isolation and reduced thermal conductance.

14. Acoustical treatment of an attic space roof vent did not improve the overall sound transmission properties of the roof/ceiling assembly.

15. Thermal conductance calculations based on ASHRAE procedures were verified in a guarded hot box test of a wall assembly.

REFERENCES

(1) H. J. Sabine, M. B. Lacher, D. R. Flynn, and T. L. Quindry, Acoustical and Thermal Performance of Exterior Residential Walls, Doors, and Windows, NBS Building Science Series 77, U. S. Government Printing Office, Washington, D.C., November 1975.

(2) "Design Guide - Methods for Improving the Noise Insulation of Houses with Respect to Aircraft Noise", Report 1390 by Bolt, Beranek and Newman, Inc., Los Angeles, California, November 1966, GPO - HH1.31:19.

(3) J. T. Weissenberger, J. C. McBryan and L. F. Heitkamp, "Airport Related Residential Insulation Demonstration Project", Report 1720, by Engineering Dynamics International, St. Louis, Missouri, June 1981, NTIS - PB 82-100777.

(4) B. H. Sharp, P. K. Kasper and M. L. Montroll, "Sound Transmission Through Building Structures - Review and Recommendations for Research", Report WR 80-20, by Wyle Research, Arlington, Virginia, July 1980, NBS - NBSIR 80-250, NTIS - PB 81 187072.

(5) "Home Soundproofing Pilot Project for the Los Angeles Department of Airports", Report WCR 70-1 by Wyle Laboratories, El Sequndo, California, March 1970.

(6) "Guide to the Soundproofing of Existing Homes Against Noise", Report WCR 70-2 by Wyle Laboratories, El Sequndo, California, March 1970.

(7) G. E. Caffey, "Residential Air Infiltration", ASHRAE Transactions, Vol. 85, Part 1, p. 41-57, 1979.

(8) J. E. Marsh, "The Airborne Sound Insulation of Glass: Part 2", Applied Acoustics, Vol. 4, p. 131-154, 1971.

(9) ASHRAE Handbook of Fundamentals, Chapter 23, American Society of Heating, Refrigerating and Air COnditioning Engineers, Atlanta, Ga., 1981.

(10) "Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions", E90-75, Vol. 18,

American Society for Testing and Materials, Philadelphia, Pa. 1975.

(11) "Determination of Sound Transmission Class", E413-73, Vol. 18, American Society for Testing and Materials, Philadelphia, Pa. 1980.

(12) "Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors", E283-73, Vol. 18, American Society for Testing and Materials, Philadelphia, Pa. 1973.

(13) "Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box", C236-80, Vol. 18, American Society for Testing and Materials, Philadelphia, Pa. 1980.

(14) "Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method", C423-81, Vol. 18, American Society for Testing and Materials, Philadelphia, Pa. 1981.

(15) "Repair and Remodeling Cost Data - 1982 (Commercial, Residential)", 3rd Annual Edition; Robert Snow Means Company, Inc., Kingston, Ma., 1982.

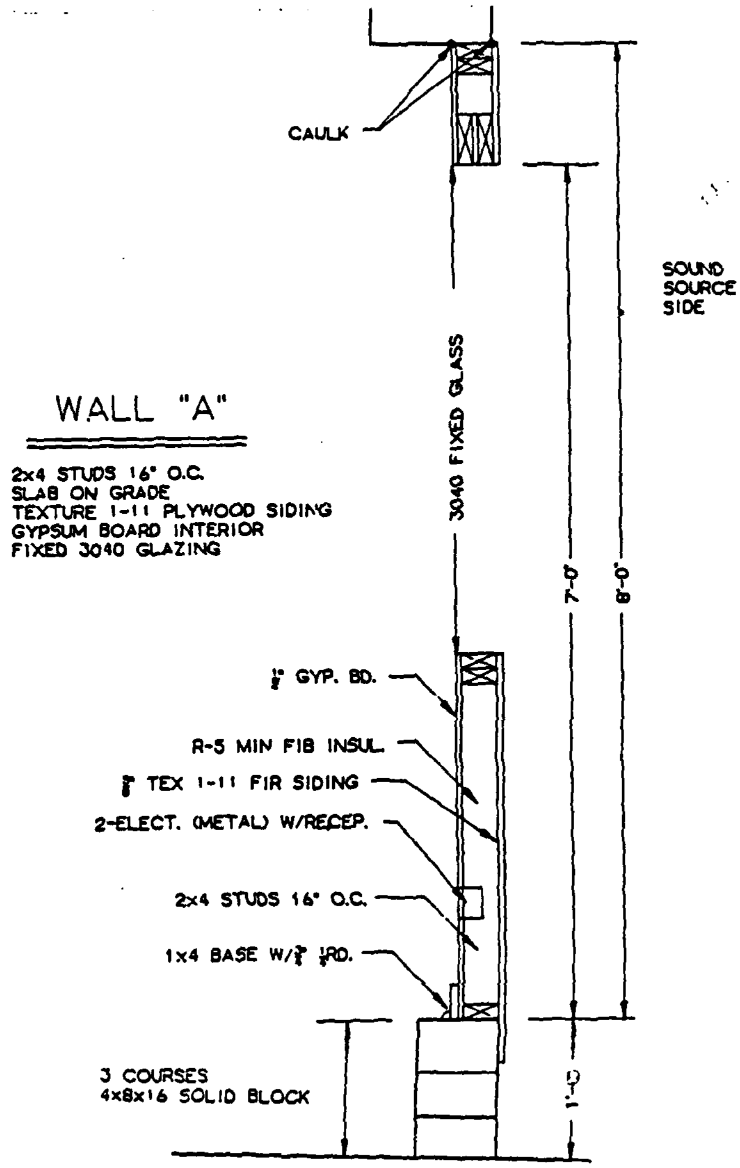
(16) "Building Construction Cost Data - 1982", 40th Annual Edition; Robert Snow Means Company, Inc., Kingston, Ma. 1982.

(17) "Federal Energy Management and Planning Programs; Methodology and Procedures for Life Cycle Costs Analyses (Average Fuel Costs)", Department of Energy, Federal Register, November 18, 1981, Part II, p. 56716-56733.

(18) D. T. Grimsrud, R. C. Sonderreger, M. H. Sherman, R. C. Diamond and Ake Blomsterberg, "A Framework for A Construction Quality Standard for Air Leakage in Residential Buildings", Lawrence Berkeley Laboratory, Berkeley, Calif., Paper - LBL 9416.

APPENDIX A

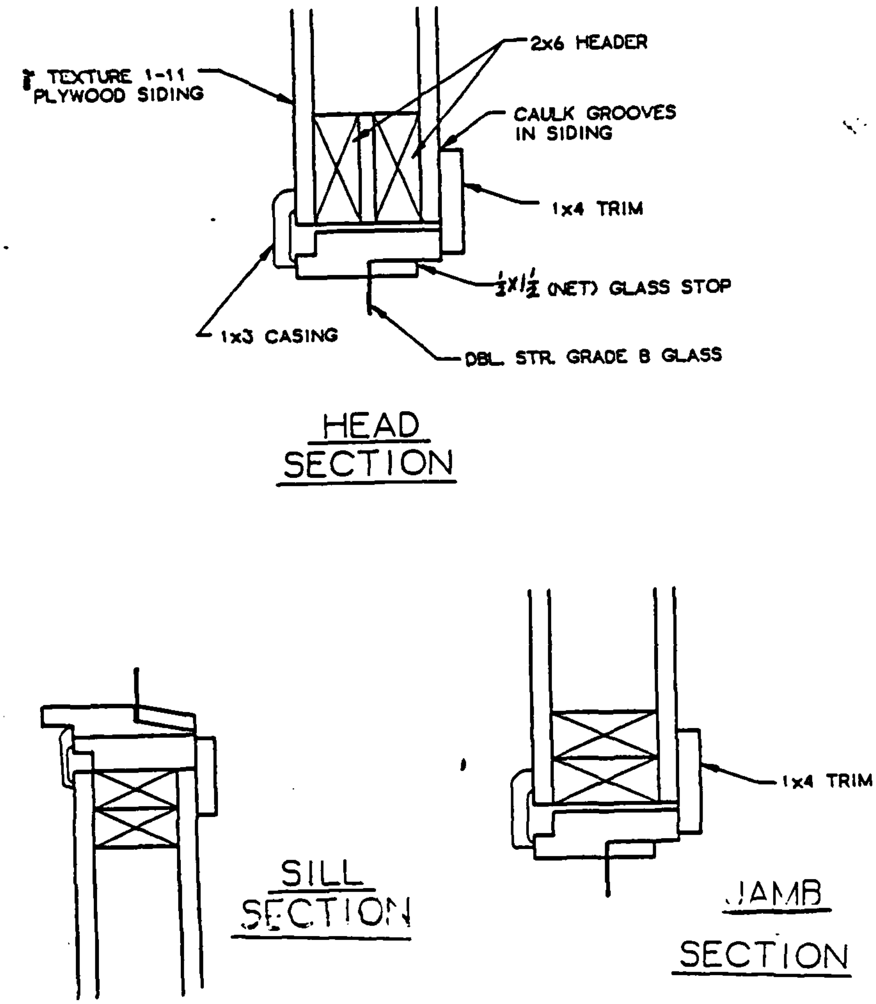
DETAILS OF WALL TEST PANEL "A"



WALL TEST PANEL "A"

FIGURE A1
1 IN. = 1FT.

C1834



SASH DETAILS OF WALL TEST PANEL "A"

FIGURE A2
3 IN. = 1FT.

C1835

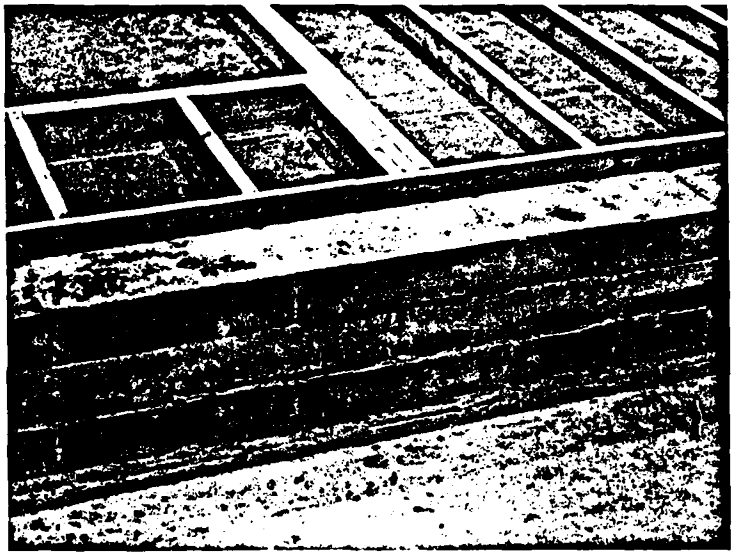


Fig. A3. Wall Framing on Laboratory Floor Showing One Foot Concrete Block Sill in Test Opening.

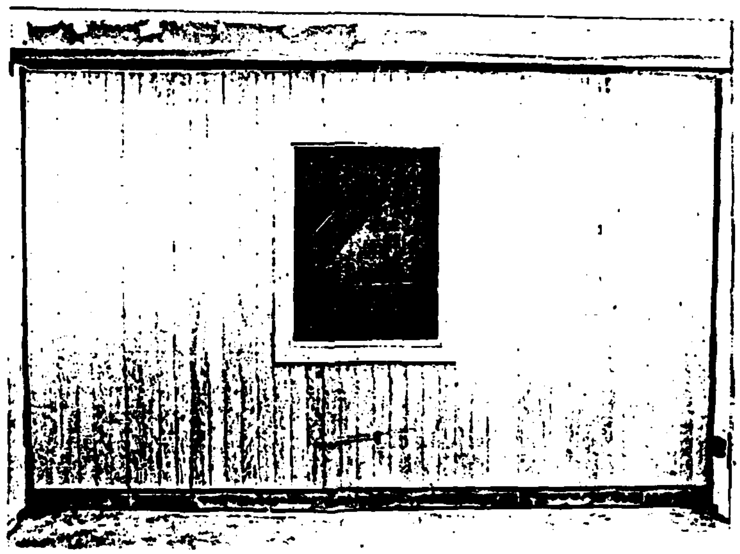


Fig. A4. Exterior of Wall Showing Texture 1-11 Siding and Original Glazing in Place.

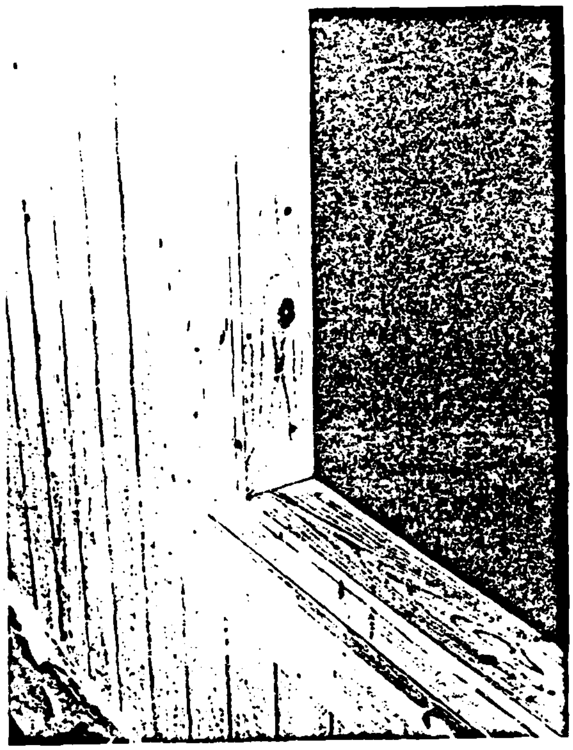


Fig. A5. Detail of Window Framing Viewed From Exterior Side.

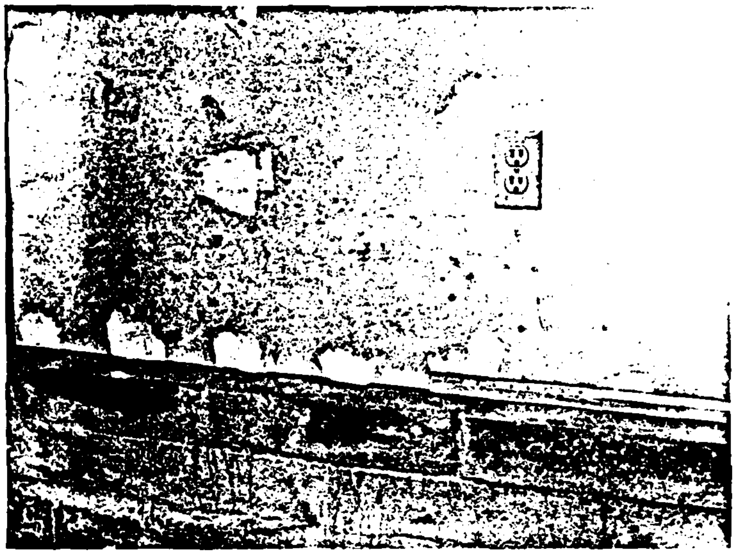


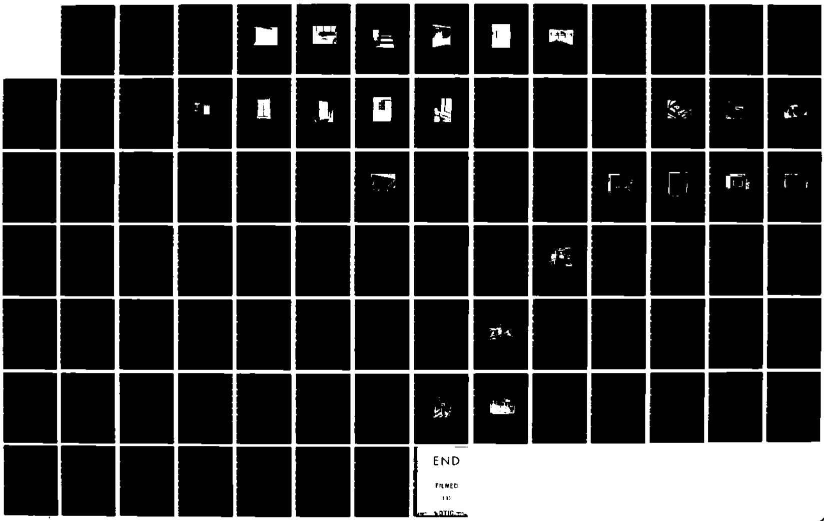
Fig. A6. Detail at Electrical Outlet on Interior Side Showing Typical Crack Between "Floor" and Gypsum Board.

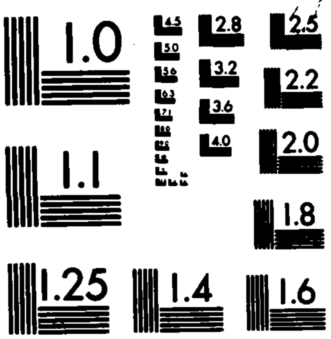
Fig. A7. Storm Window and Frame.

Fig. A8. Additional Insulation Added to Interior Wall Surface.

AD-A131 879 ACOUSTICAL BENEFITS RESULTING FROM INSULATION AND AIR LEAKAGE CONTROL IN..(U) MANVILLE SERVICE CORP DENVER CO RESEARCH AND DEVELOPMENT CENT.. J D VERSCHOOR ET AL. 2/2

UNCLASSIFIED JUL 83 NCEL-CR-83.019 N62583-82-MT-033 F/G 5/5 NL

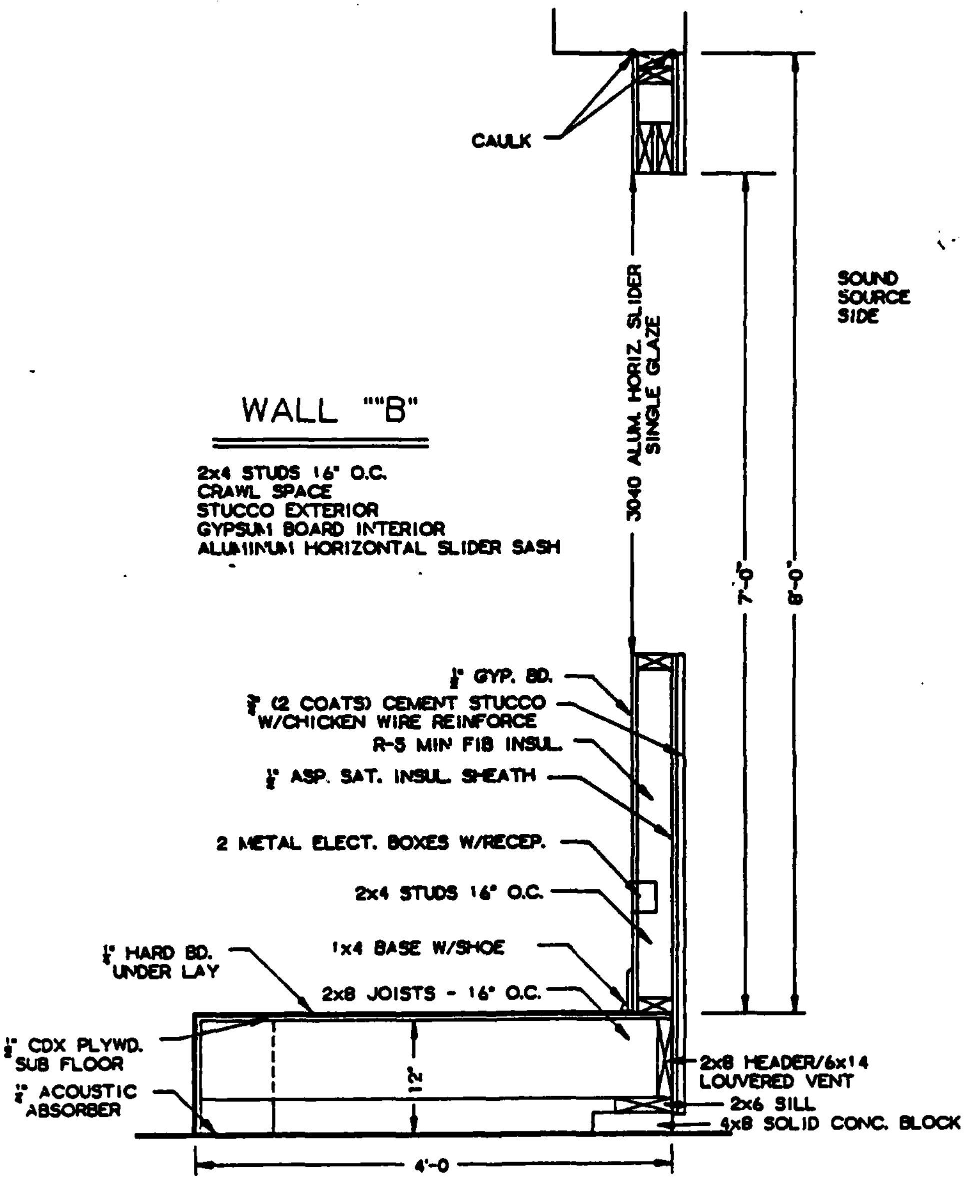




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

APPENDIX B

DETAILS OF WALL TEST PANEL "B"



WALL TEST PANEL ""B"

FIGURE B1
1 IN. = 1FT.

C1836

Fig. B2. Basic Wall Framing Viewed From Interior Side Showing Crawl Space.

Fig. B3. Framing of Wall Viewed From Exterior Side Showing Header.

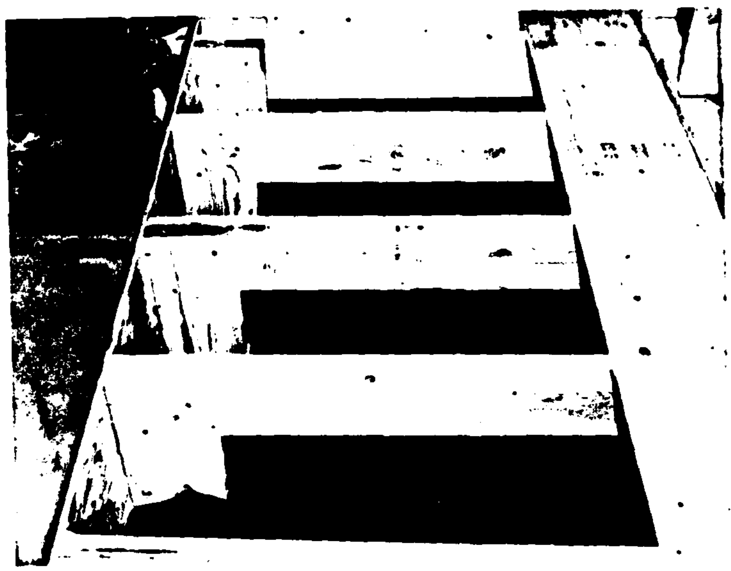


Fig. B4. Crawl Space Framing.

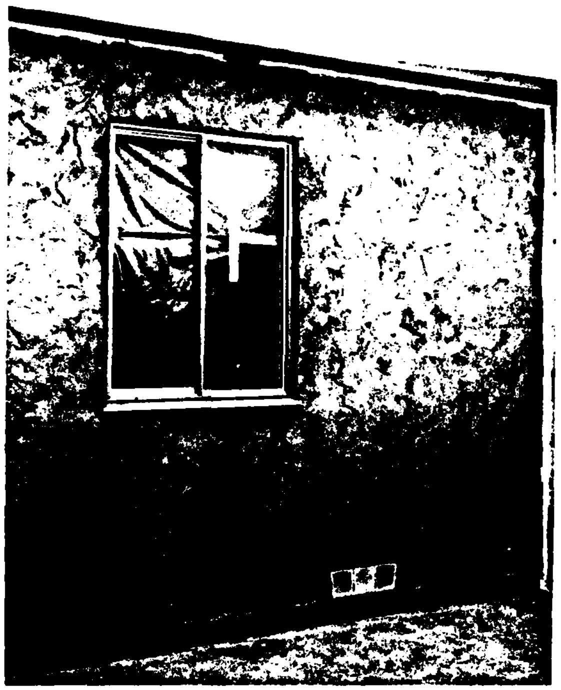


Fig. B5. View of Exterior Showing Prime Window and Crawl Space Vent (Plastic film over window for calibration tests only).

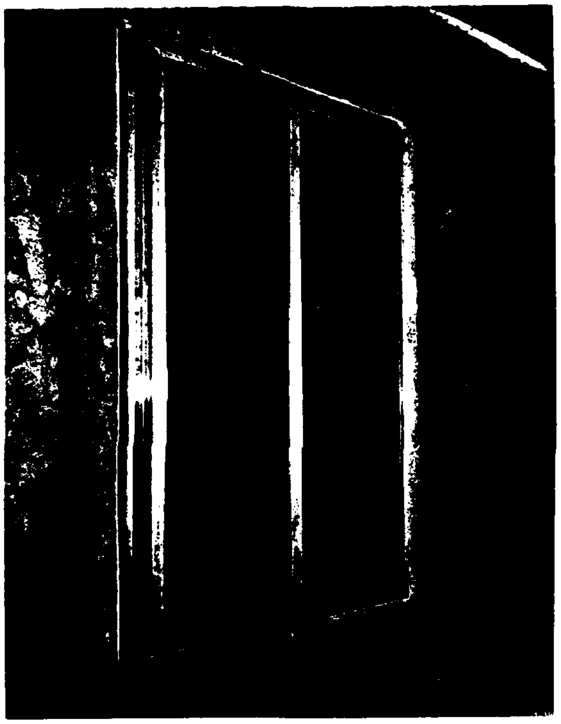


Fig. B6. Aluminum Storm Window Installed Over Prime Window.

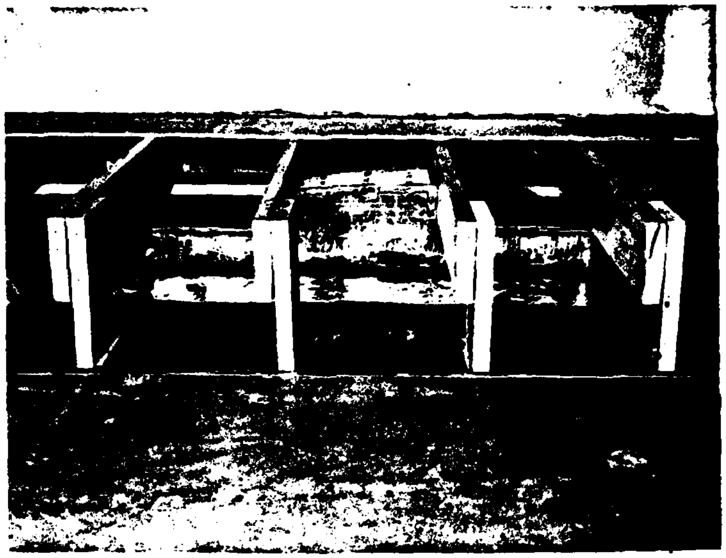
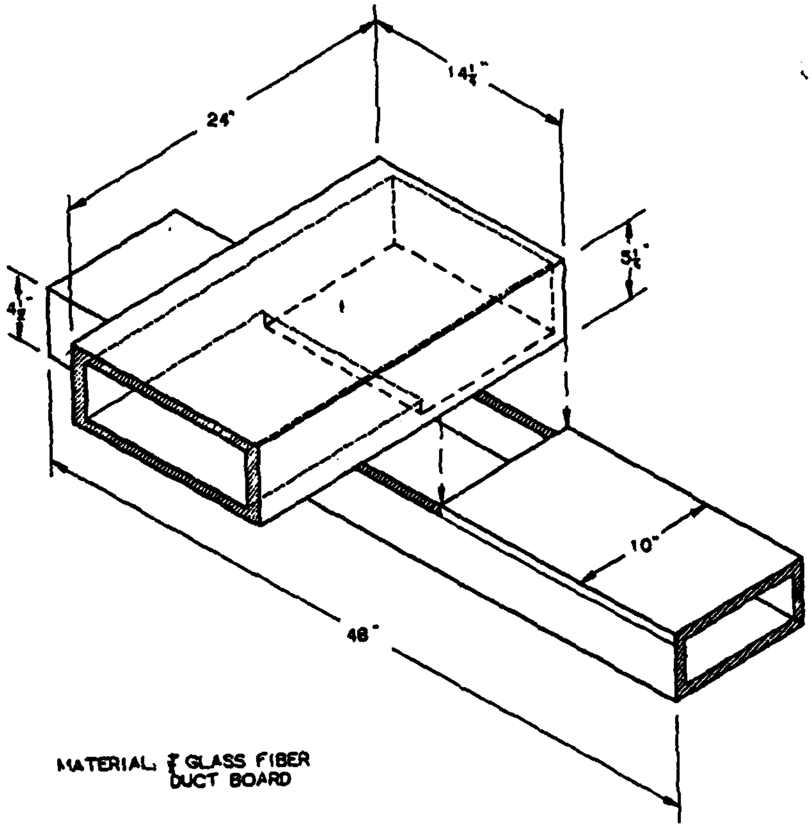


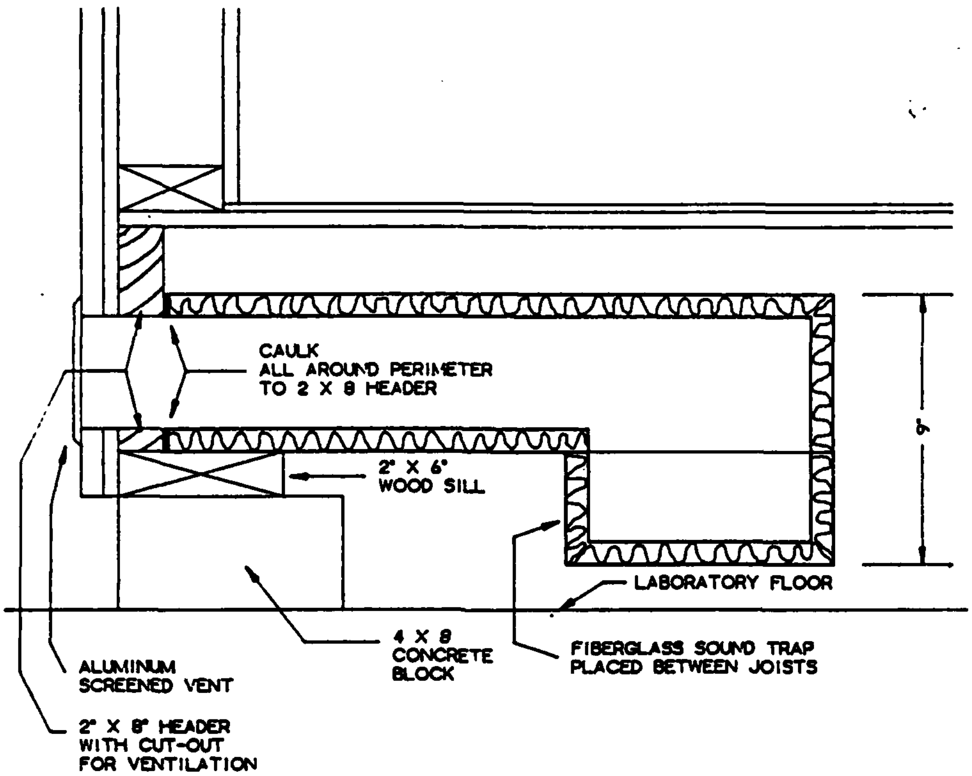
Fig. B7. Crawl Space Vent Baffle in Place.



CRAWL SPACE VENT SOUND TRAP

FIGURE 88
1-1/2" = 1 FT.

C1837



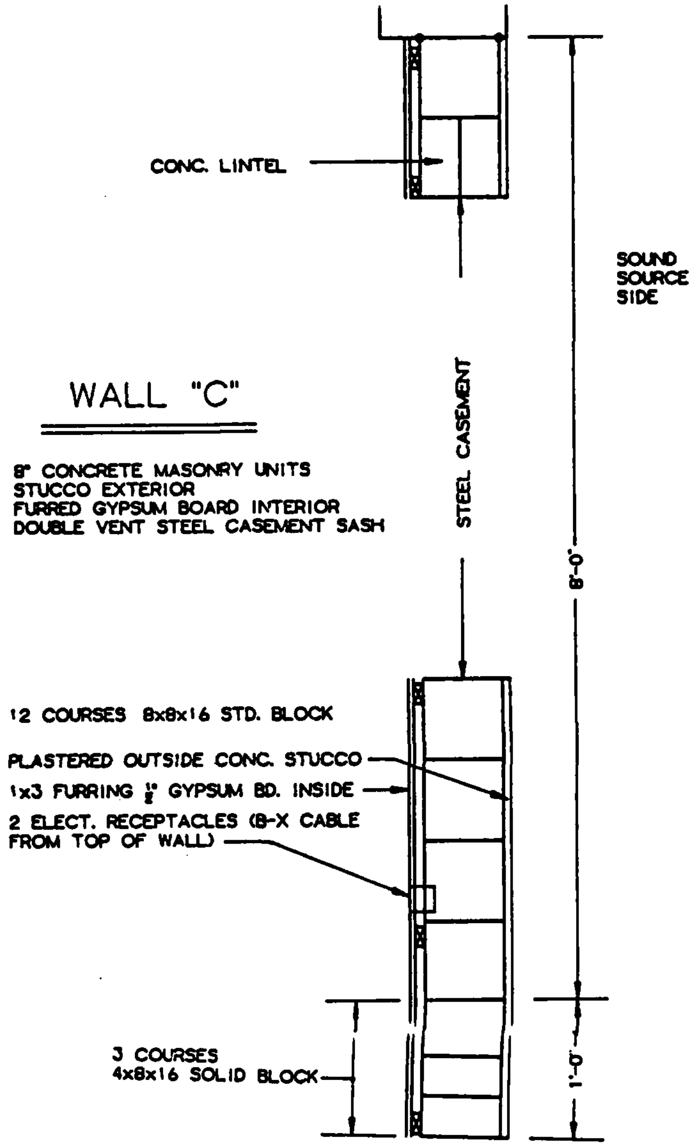
INSTALLATION OF CRAWL SPACE SOUND TRAP VENT

FIGURE 89
3 IN. = 1FT.

C1838

APPENDIX C

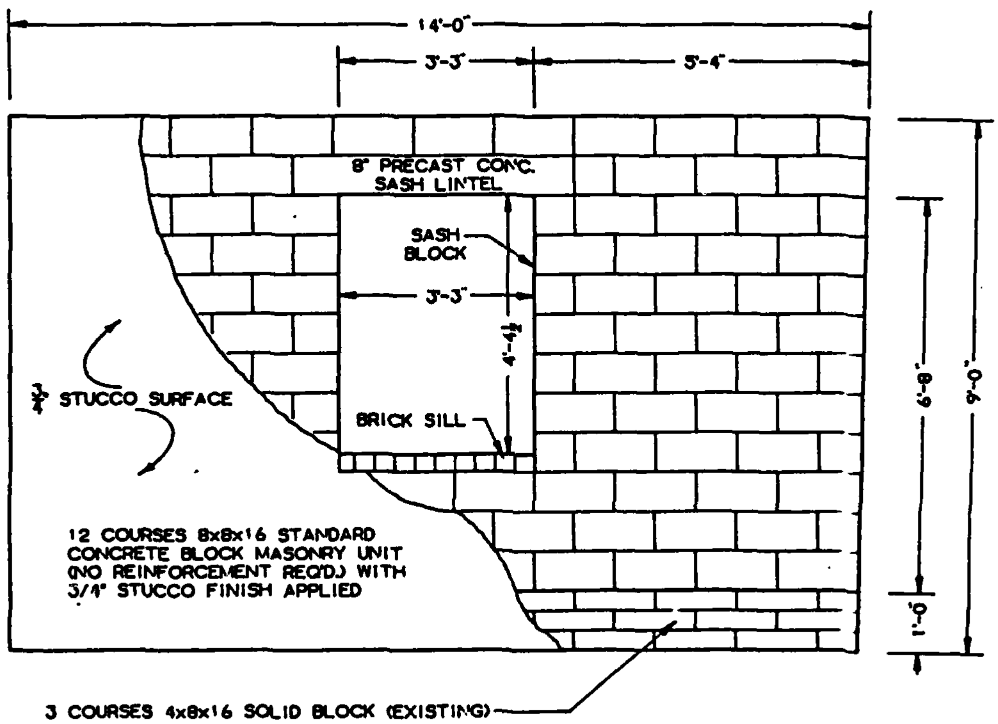
DETAILS OF WALL TEST PANEL "C"



WALL TEST PANEL "C"
SECTION VIEW

FIGURE C1
1 IN. = 1FT.

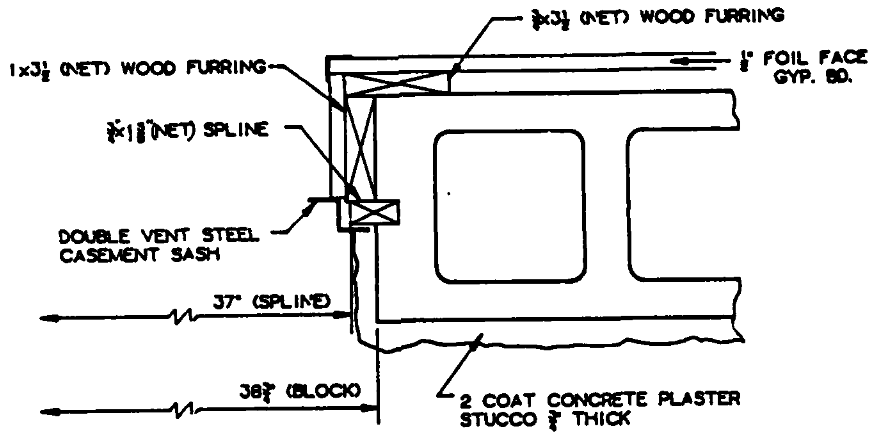
C1839



WALL TEST PANEL "C" - ELEVATION VIEW

FIGURE C2
1/2 IN. = 1FT.

C1840



WALL TEST PANEL "C" - WINDOW DETAIL

FIGURE C3
3 IN. = 1FT.

C1841

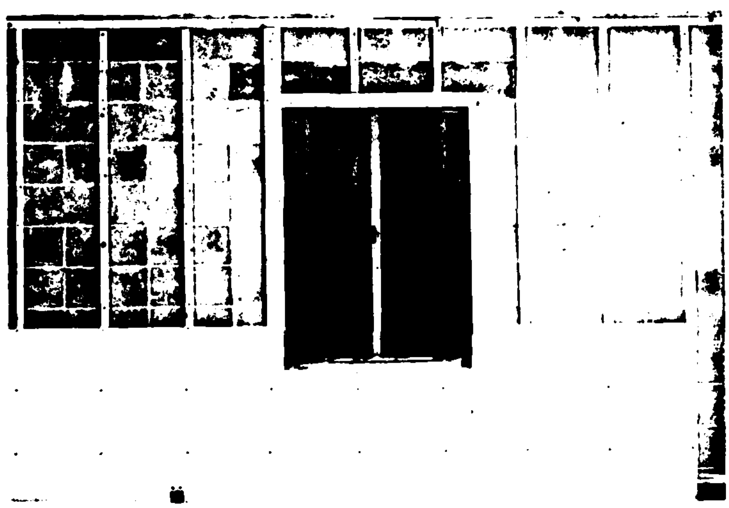


Fig. C4. Interior Surface Showing Wood Furring Strips, Gypsum Board and Steel Sash Window.

Fig. C5. Steel Sash Window Installation.

Fig. C6. Aluminum Replacement Window Viewed from Exterior.

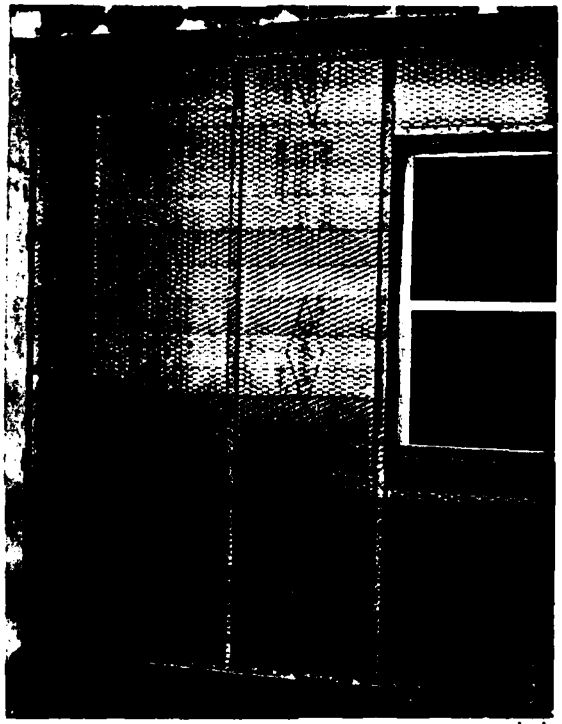
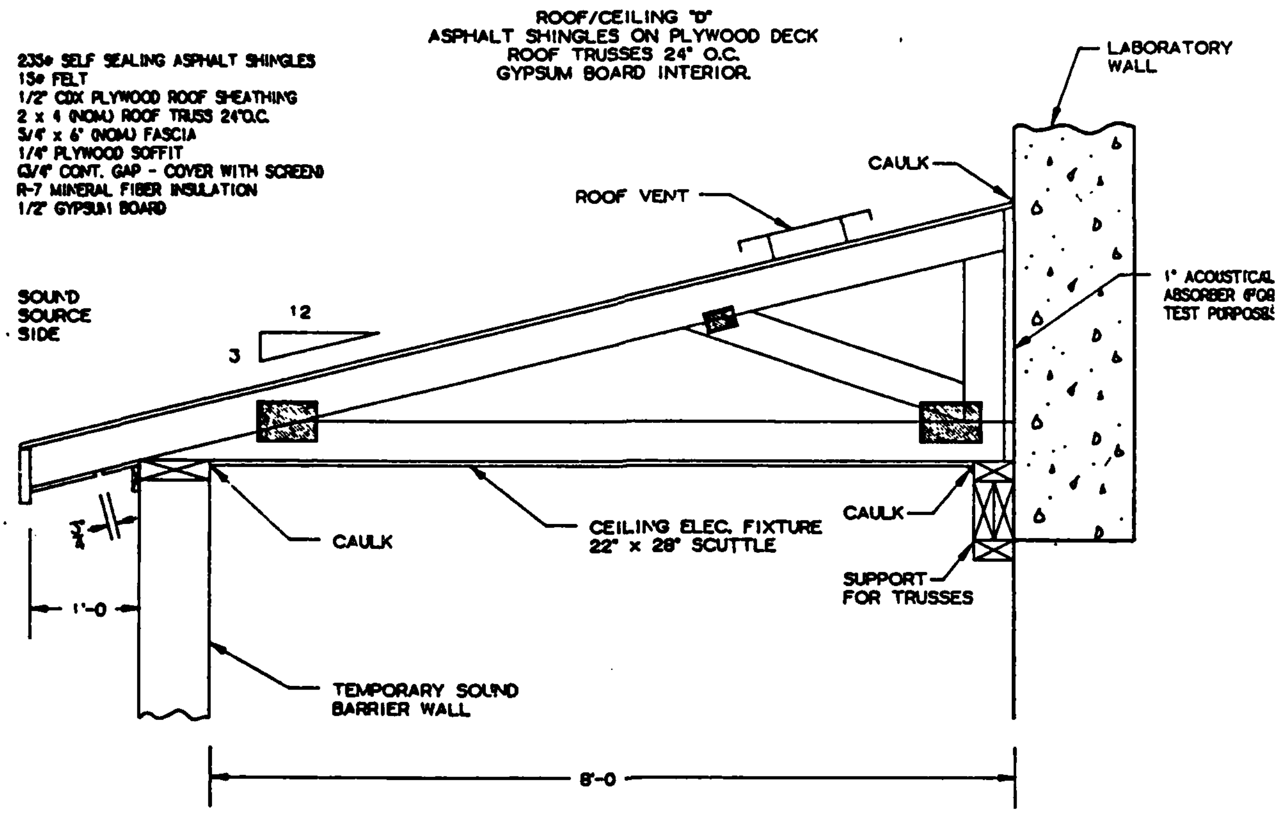


Fig. C7. Installation of 1 1/2" Polystyrene Insulation Over Exterior Surface Showing Furring, Insulation and Wire Lath for Application of Stucco.

Fig. C8. Detail at Window Showing Installation of 1 1/2" Polystyrene Insulation (Window sill not modified at this point in retrofit).

APPENDIX D

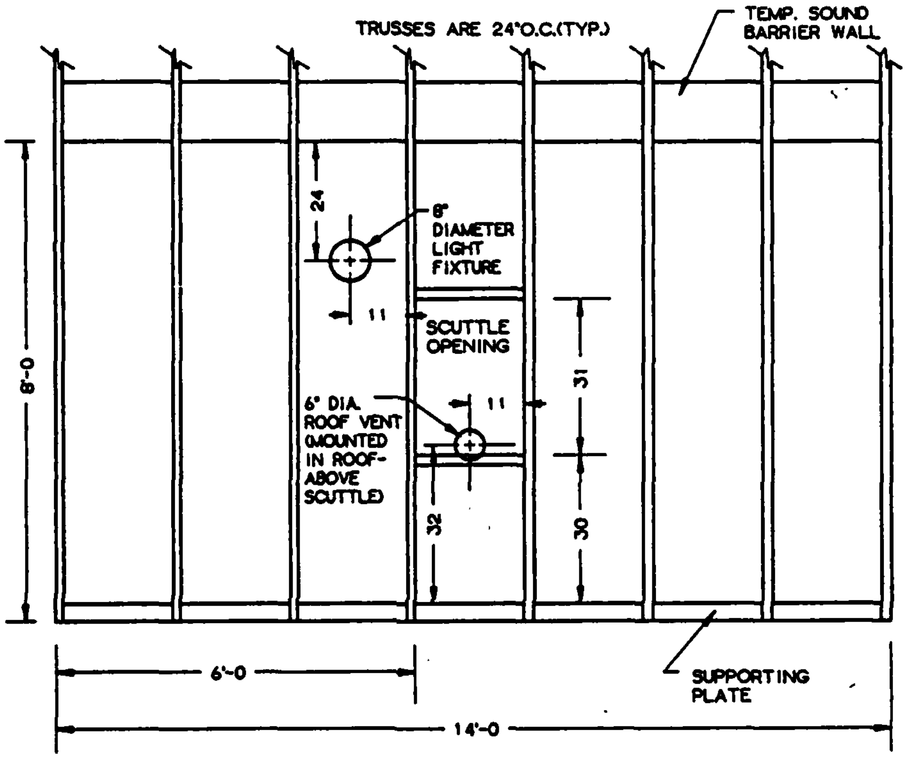
DETAILS OF ROOF/CEILING TEST PANEL "D"



ROOF/CEILING TEST PANEL "D"

FIGURE D1

C1830



REFLECTED CEILING PLAN
FOR TEST PANEL "D"

FIGURE D2
$\frac{1}{2}$ IN. = 1 FT.

C1833

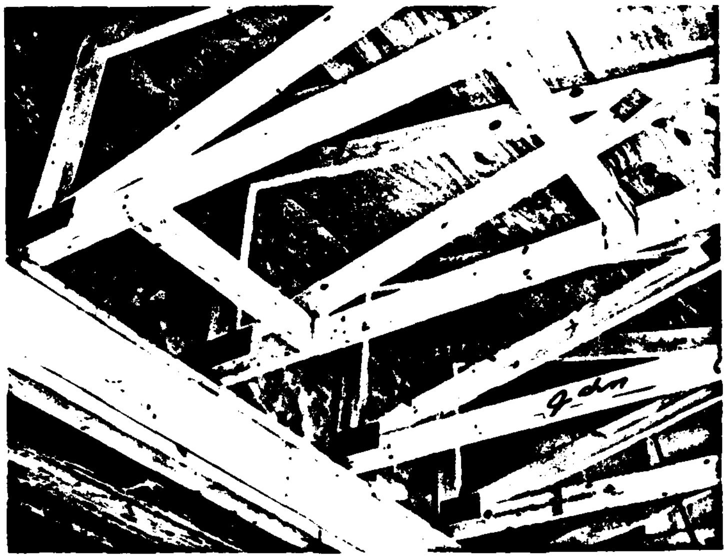


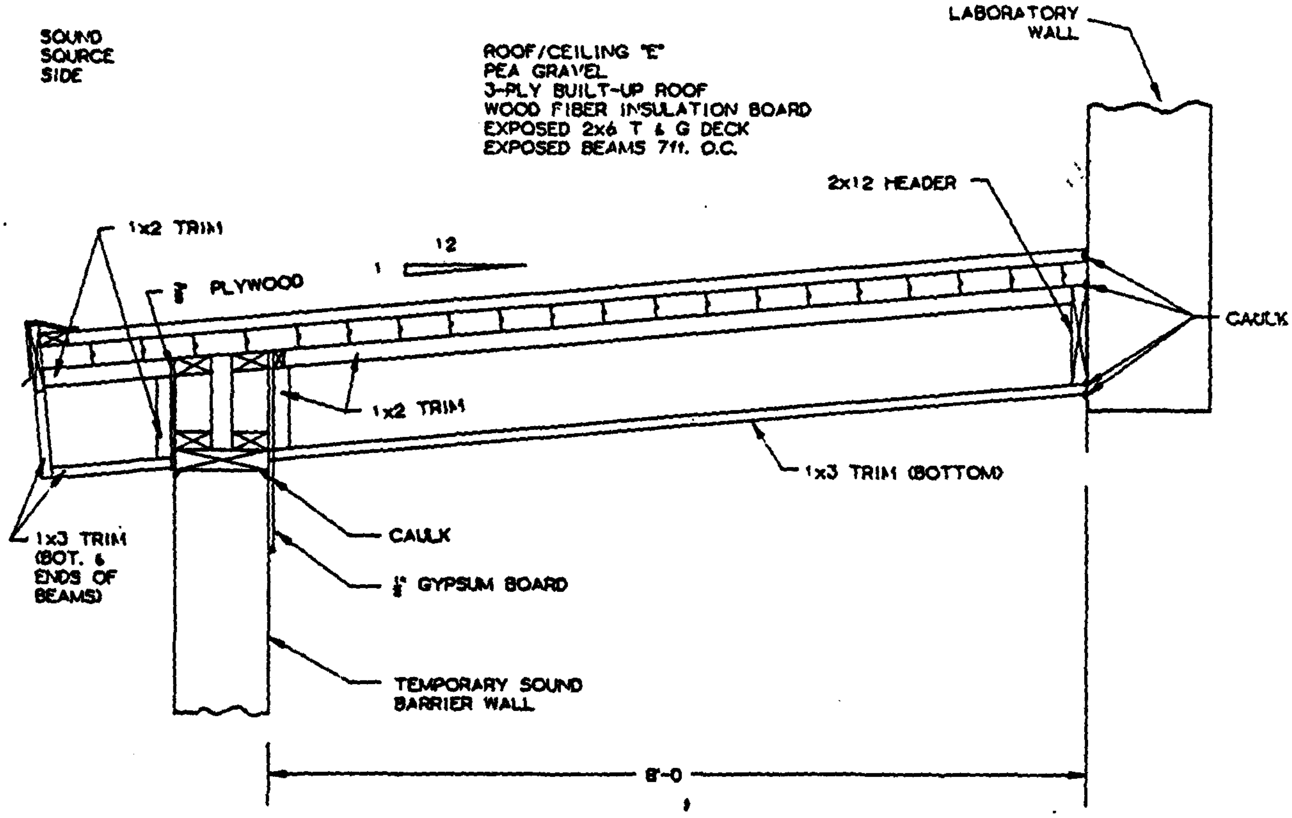
Fig. D3. Wood Trusses in Place Showing Location of Scuttle and Cut-Out for Roof Vent Directly Above Scuttle.

Fig. D 4. Retrofit Dropped Ceiling in Place Showing Detail at Scuttle.

Fig. D5. Retrofit Dropped Ceiling Showing Scuttle Seal.

APPENDIX E

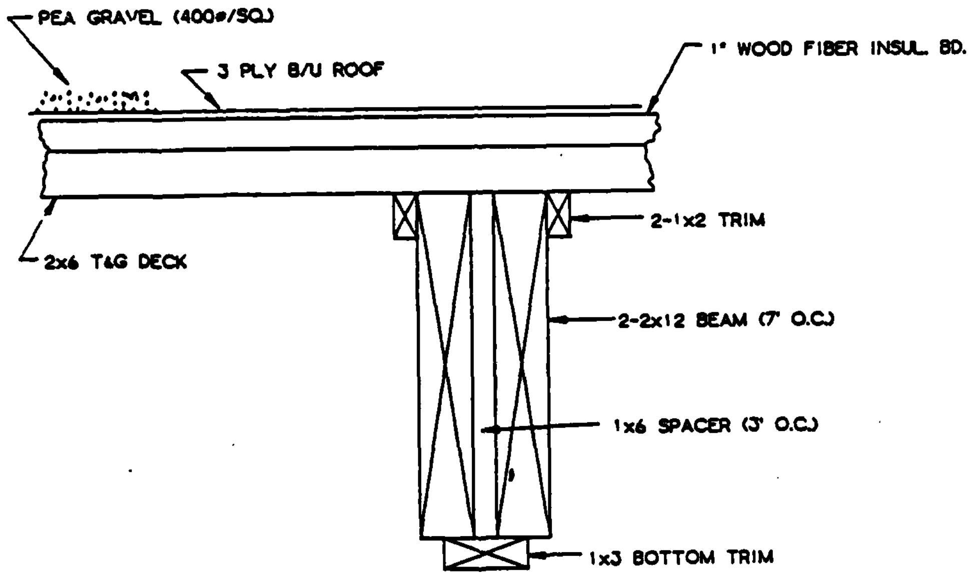
DETAILS OF ROOF/CEILING PANEL "E"



ROOF/CEILING TEST PANEL "E"

FIGURE E1

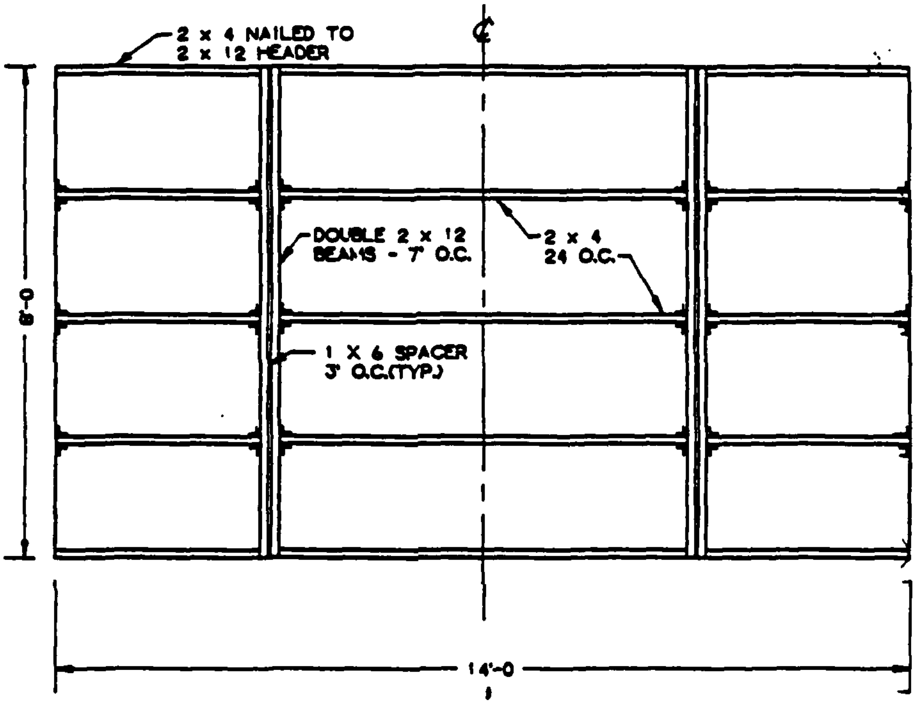
C1842



ROOF/CEILING TEST PANEL "E"
DECK/BEAM DETAIL

FIGURE E2
3 IN. = 1FT.

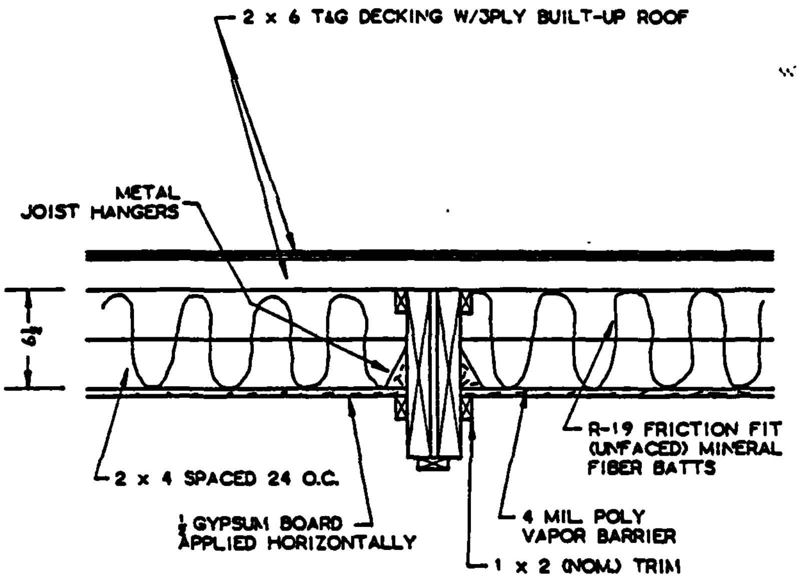
C1843



REFLECTED CEILING PLAN
FOR RETROFIT E2

FIGURE E3
$\frac{1}{2}$ IN. = 1 FT.

C'832



SECTION OF RETROFIT E2

FIGURE E4
1½ IN. = 1 FT.

C1831

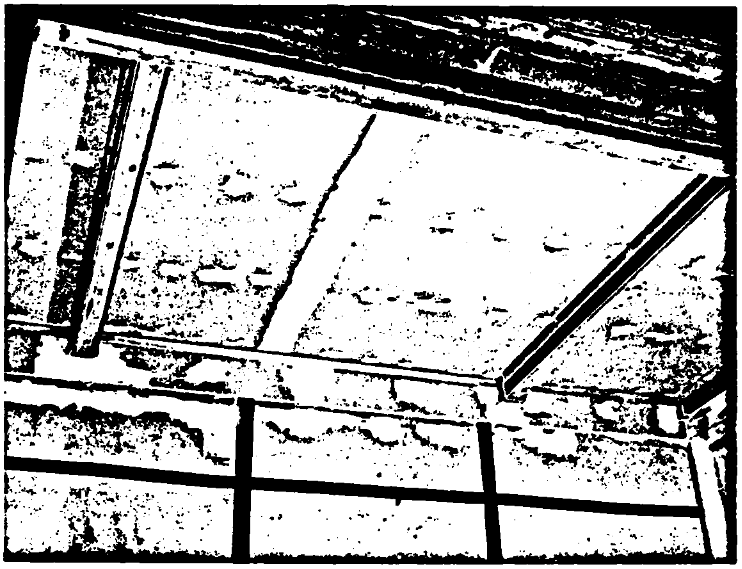
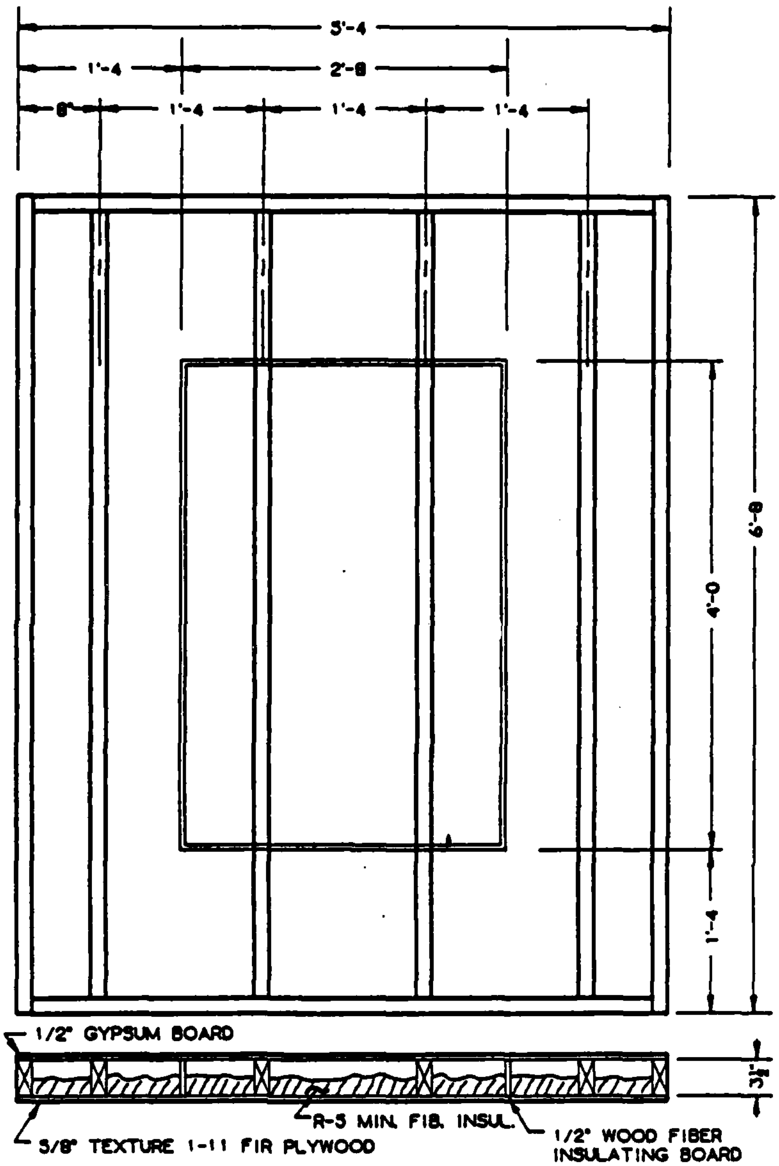


Fig. E 5. Retrofit Dropped Ceiling Installed.

APPENDIX F

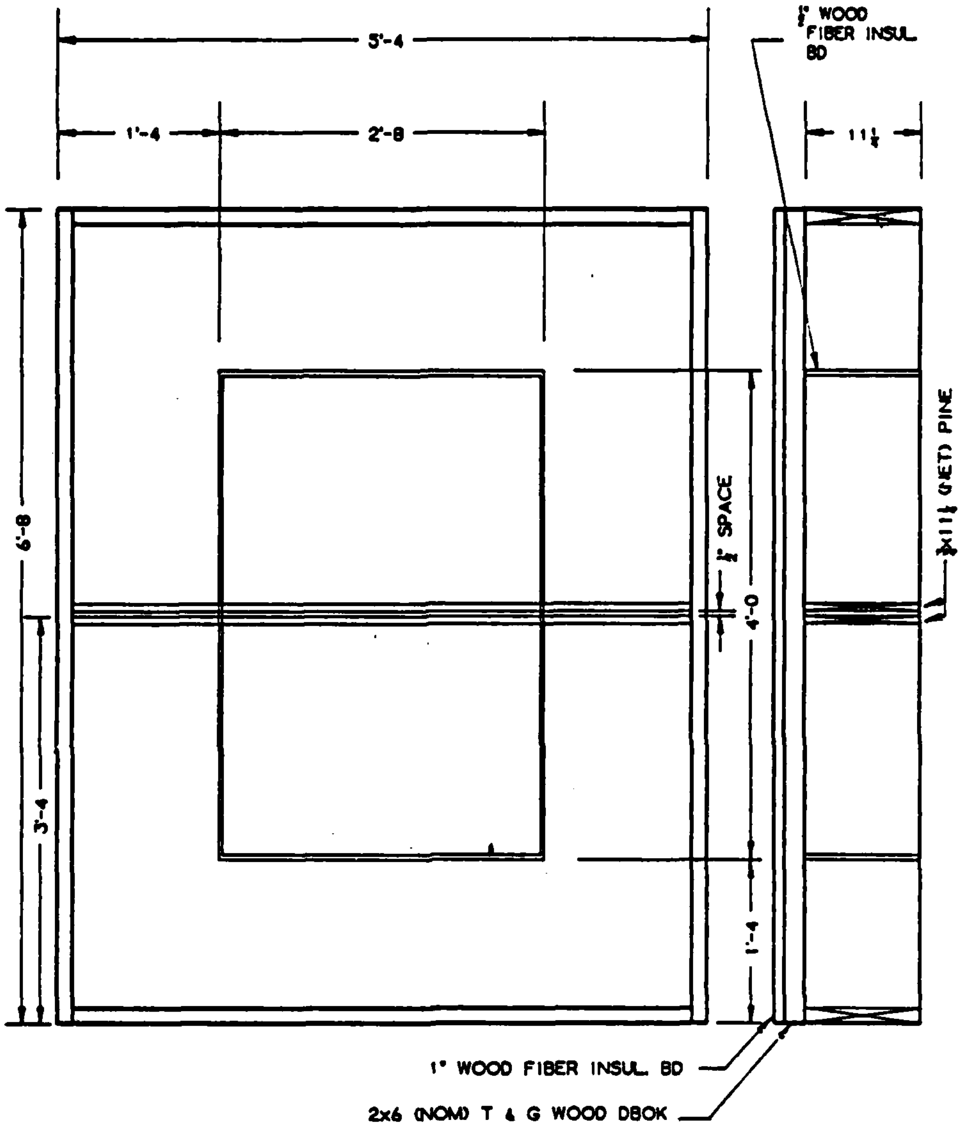
DETAILS OF THERMAL TEST PANELS "A" AND "E"



THERMAL TEST PANEL "A"

FIGURE F1
1 IN. = 1FT.

C1844



THERMAL TEST PANEL "E"

FIGURE F2
1 IN. = 1FT.

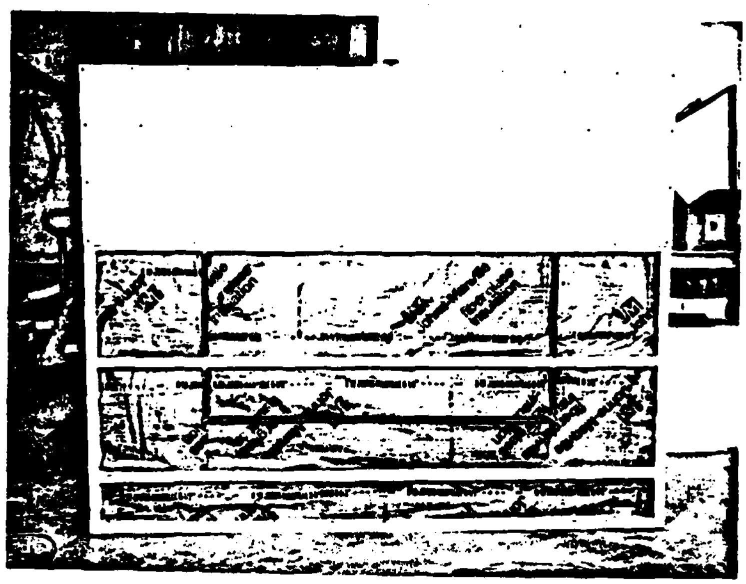


Fig. F3. Texture 1-11 Plywood Siding on Wood Frame Wall Showing Interior Side, Insulation and Gypsum Board.

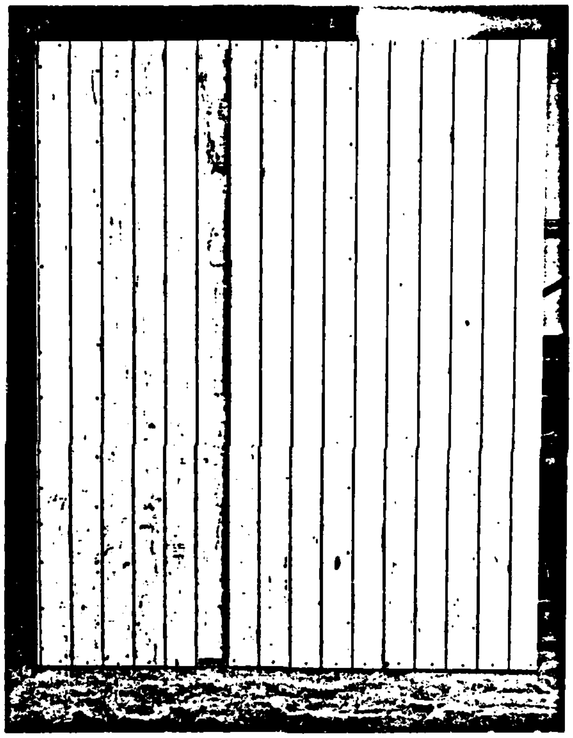


Fig. F4. Texture 1-11 Plywood Siding on Wood Frame Wall Showing Exterior Side.

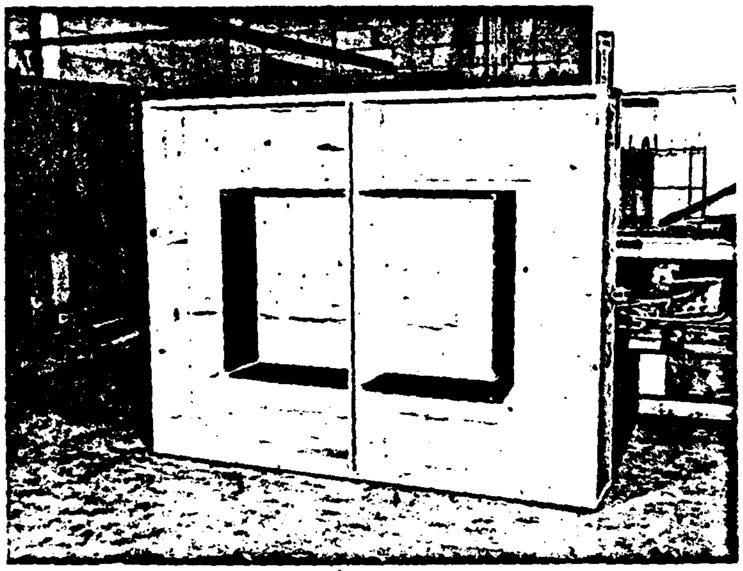


Fig. F5. T&G Wood Decking over 2 by 12 Beams Showing Interior Surface and Convection Guard.

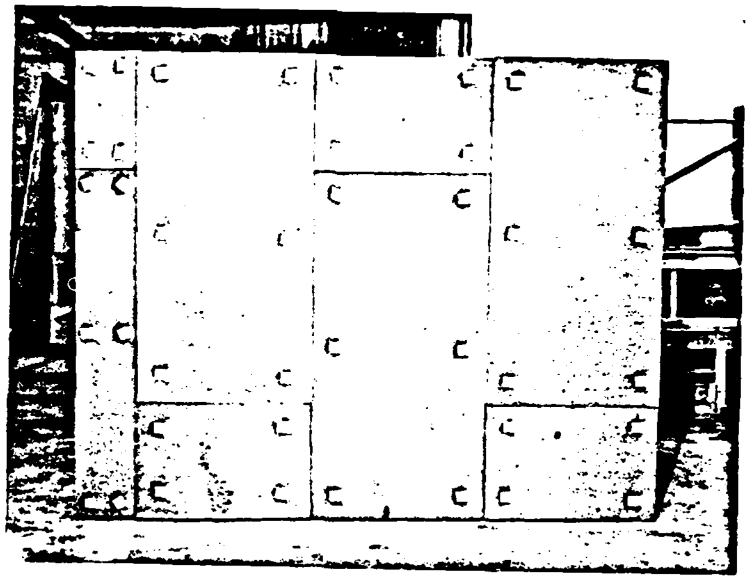


Fig. F6. T&G Wood Decking over 2 by 12 Beams Showing 1 inch Wood Fiber Insulation on Exterior Side of Panel.

APPENDIX G

SOUND TRANSMISSION LOSS TEST PROCEDURE

APPENDIX G

SOUND TRANSMISSION LOSS TEST PROCEDURE

The random incidence sound transmission loss (TL) properties of each test specimen were determined in accordance with the provisions of ASTM "Standard Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions", designation E90-75.* The sound transmission loss is the ratio of the sound power incident on a surface to the power radiated by the opposite side of the surface, expressed on a logarithmic scale.

A single number rating of performance based on the measured individual sound transmission loss values at each frequency, identified as the Sound Transmission Class (STC), was determined in accordance with ASTM "Standard Classification for Determination of Sound Transmission Class" designation E 413-73[11] (Reapproved 1980). The Sound Transmission Class rating has been designed to correlate with subjective impression of sound isolation.

In this test (reference Figure G1), a specimen of area S is constructed as a partition separating two large reverberant rooms. High level, random noise is generated in the "Source" room which faces the side of the specimen representing the exterior building surface. A portion of the sound energy incident on the specimen surface passes through the panel into the "Receiving" room. The difference between the "Source" and "Receiving" room sound levels is measured in eighteen one-third octave wide bands covering the center band frequency range of from 100 to 5000 Hz. The individual differences in room sound levels are identified as Noise Reduction (NR) values and are used in the calculation of transmission loss (TL) as described below.

---

* "Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions", E90-75, Vol. 18, American Society for Testing and Materials, Philadelphia, Pa. 1975.

The magnitude of the NR values is a function of the test specimen area, the specimen transmission loss and the amount of sound absorption in the "Receiving" room. For this reason, it is necessary to measure the receiving room sound absorption as part of the transmission loss test. This is accomplished using the decay rate method described in ASTM "Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method" designation C423-81.*

The sound transmission loss of the test specimen in each of the eighteen one-third octave wide bands is determined in accordance with the following expression:

$$TL = NR + 10 \log (S/A) \tag{G1}$$

where:

TL = transmission loss, decibels (dB)
NR = noise reduction, decibels
S = specimen area, square feet
A = receiving room sound absorption, sabins
log = logarithm to the base 10

In order to facilitate the large number of measurements and computations made under this project, a computer program was written which accomplished the following basic functions:

1. Microphone calibrations to eliminate the effects of microphone sensitivities on measured NR Values.

2. Determination of receiving room sound absorption.

3. Noise reduction measurements.

---

* "Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method", C423-81, Vol. 18, American Society for Testing and Materials, Philadelphia, Pa. 1981.

4. Background (ambient) noise determinations and corrections.

5. Sound Transmission Loss (TL) calculations.

6. Calculation of TL measurement precision.

7. Sound Transmission Class (STC) determinations.

8. Data and specimen identification storage on magnetic tape.

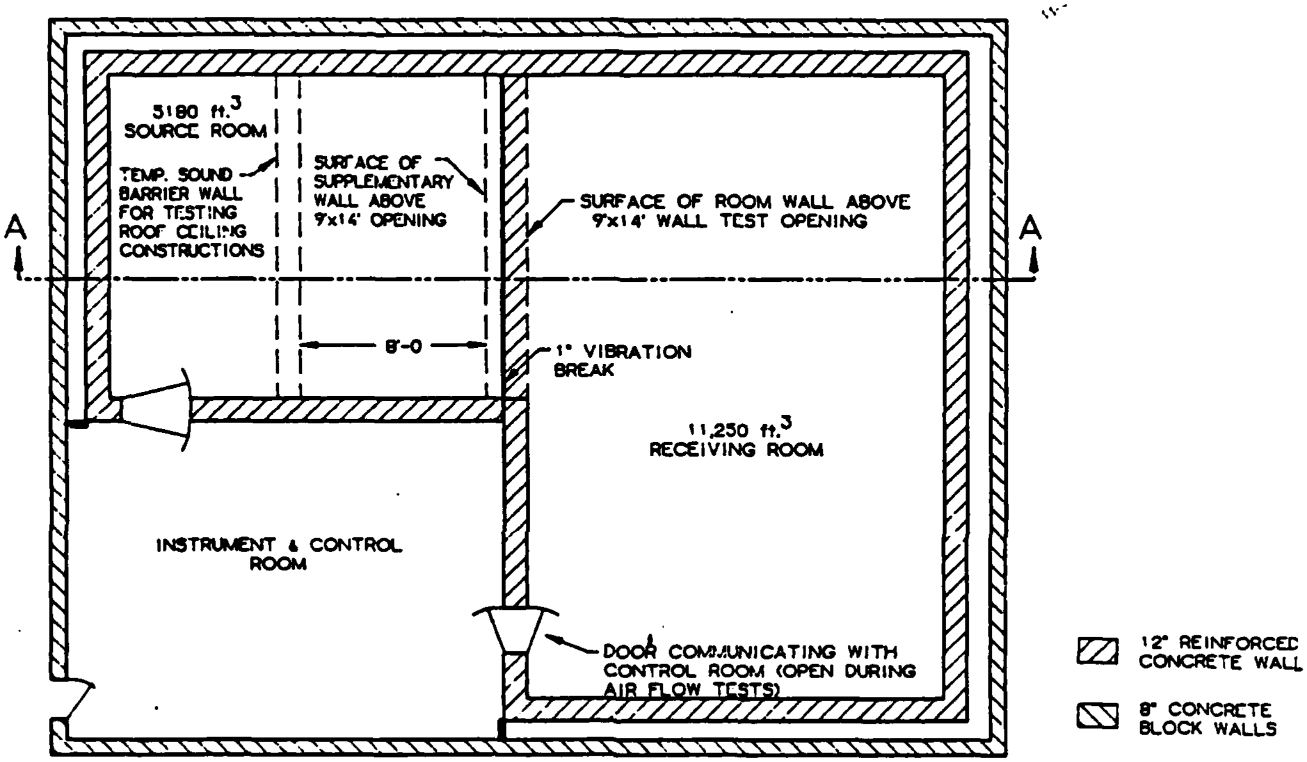
A complete description of the computer program architecture is documented in Johns-Manville Research and Development Center Memorandum report M-492-37 dated January 27, 1982. Details pertinent to the calculation of the Sound Transmission Loss (TL) and Sound Transmission Class (STC) values as well as to the calculation of measurement precision are given under the "Calculations" section of this Appendix. Figures G7a and G7b show a typical computer printout as made available at the end of a test.

A description of the test facility follows.

Test Chambers

The Source and Receiving rooms utilized for these measurements are shown in plan and elevation views in Figures G1 and G2 respectively. Both rooms are formed with 12 inch thick, reinforced concrete walls which are surrounded on three sides by an eight inch masonry block wall which is separated from the reinforced concrete wall by an eight inch air space. The rooms are supported on separate, 12 inch thick concrete foundations and are capped with 12 inch thick concrete slabs forming separate ceilings. The interior wall surfaces of each room are coated with lime plaster and are painted to form dense, reflective surfaces thus assuring a reverberant sound field.

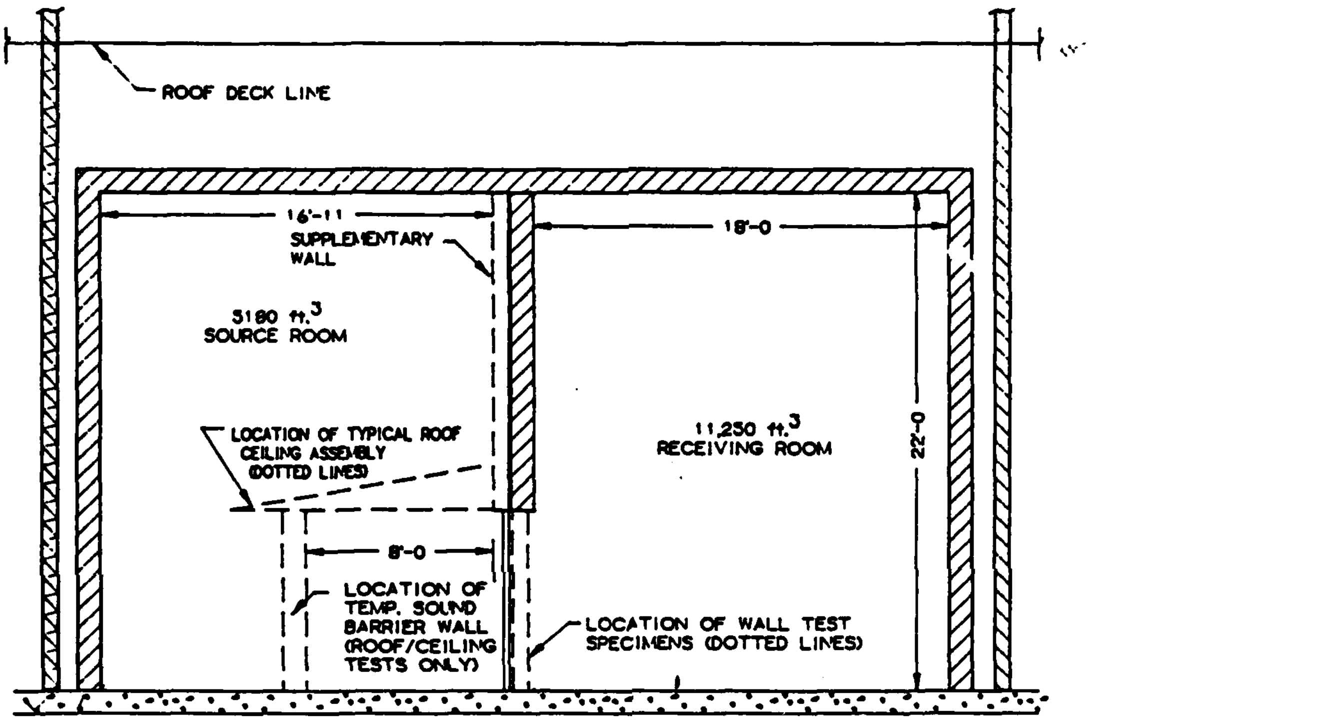
The rooms share a twelve inch thick reinforced concrete dividing wall which is physically connected to the sides and ceiling slab of the larger room. The rooms communicate



PLAN VIEW OF TEST CHAMBERS

FIGURE G1
3/16 IN. = 1FT.

C1846



TEST CHAMBERS-VERTICAL SECTION A-A

FIGURE G2
3/16 IN. = 1FT.

C1847

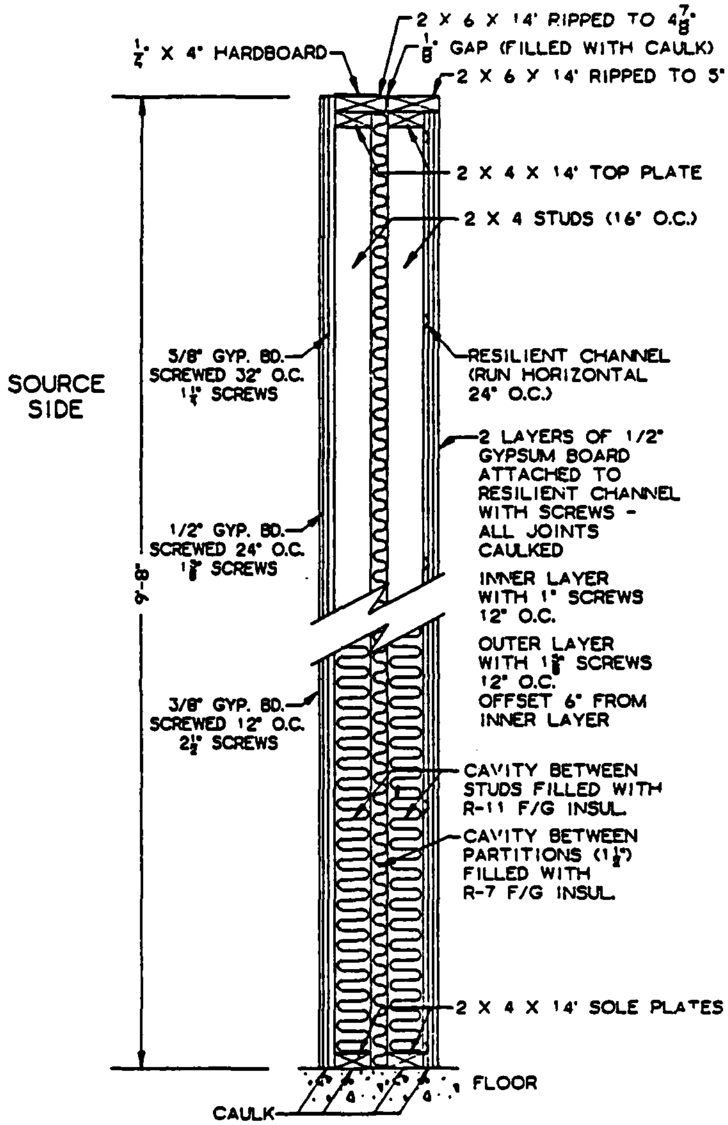
via a nine foot high by fourteen foot wide opening formed at the bottom of the dividing wall. The Source room floor, sidewalls and ceiling slab are vibration isolated from the Receiving room structure by a one inch space which is filled with concrete expansion joint material. The Source Room side of the common wall is covered by an auxiliary wall consisting of two layers of 5/8 inch gypsum wallboard applied over 6 inch metal studs. The studs are positioned horizontally and are spaced 24 inches on center. The studs are fastened to metal runner tracks which are in turn fastened to the sidewalls and ceiling slab of the source room. The runner tracks are spaced one inch away from the concrete wall separating the two rooms so that no contact is made between the auxiliary wall and the concrete dividing wall. The space between the concrete dividing wall and auxiliary wall gypsum board is filled with two layers of 3 inch thick fiberglass blanket.

The purpose of the auxiliary wall treatment is to reduce the amount of sound transmitted through the dividing wall so that measured values of room to room sound transmission are determined principally by the amount of sound passing through the test specimen (see "Corrections for Flanking Effects" section of this Appendix).

In the case of wall test panel designs A, B and C (reference Appendices A, B and C respectively) the test panels were constructed within the nine foot by fourteen foot opening immediately beneath the concrete wall separating the Source and Receiving rooms.

In the case of roof-ceiling test panel designs D and E, (reference Appendices D and E respectively), the test panels were positioned horizontally and extend into the Source room as shown in figure G2. For these tests, it was necessary to construct a temporary partition of very high sound transmission loss at a distance of eight feet from the auxiliary wall in order to support one edge of the test specimen. The opposite edge was supported using two by six inch wood plates which were supported by four by four inch wood columns.

The supporting partition design was selected to assure that the amount of sound entering the receiving room via this partition was insignificant compared with the amount of sound passing through the roof/ceiling test panel. The design of this partition is shown in Figure G3.



VERTICAL CROSS SECTION
HIGH TL WALL

FIGURE G3
1 IN. = 1 FT.

C'870

In the case of both the wall and the roof-ceiling specimens, the source and receiving room volumes were found to be sufficiently large to achieve an adequately diffuse sound field at all one-third octve band center frequencies of 100 Hz and above as defined in section 6.2.1 of ASTM E90-75.

In order to further increase the diffusion of sound within the receiving room, the room sidewalls were equipped with nine stationary, corrugated fiberglass diffusing panels arranged in a random pattern and set at oblique angles with respect to the major surfaces. In addition, the receiving room was equipped with a large rotating vane which revolved at a rate of 4.5 RPM during testing.

The Source room was equipped with four stationary, corrugated fiberglass diffusing panels. No rotating diffuser was used in the Source room.

Test Signal Generation and Measurement Apparatus

The electronics associated with generation and measurement of the test signals are shown in Figure G4. The apparatus is described below.

Signal Generation System: The test signal consisted of pink weighted (-3dB/octave) random noise derived from a General Radio type 1382 Random Noise Generator. The generator output was passed through an Altec type 1650, one-third octave band audio frequency equalizer, which was used to shape the Source room sound spectrum in order to provide a flat, one-third octave band spectrum over the frequency range of 100 - 5000 Hz. The output of the equalizer was connected to an Altec type 1609 biamplifier equipped with separate 100 watt low frequency and 50 watt high frequency amplifiers. The biamplifier was in turn connected to a Klipsch Heresy type HD-BB three way loudspeaker and an Altec type 802-8D driver which was attached to an Altec type 32B sectoral horn. The Klipsch loudspeaker and Altec horn were positioned facing the southeast lower trihedral corner of the Source room, as shown in Figures G1 and G2.

During the tests, the test signal was adjusted so as to provide a Source room sound pressure level of approximately

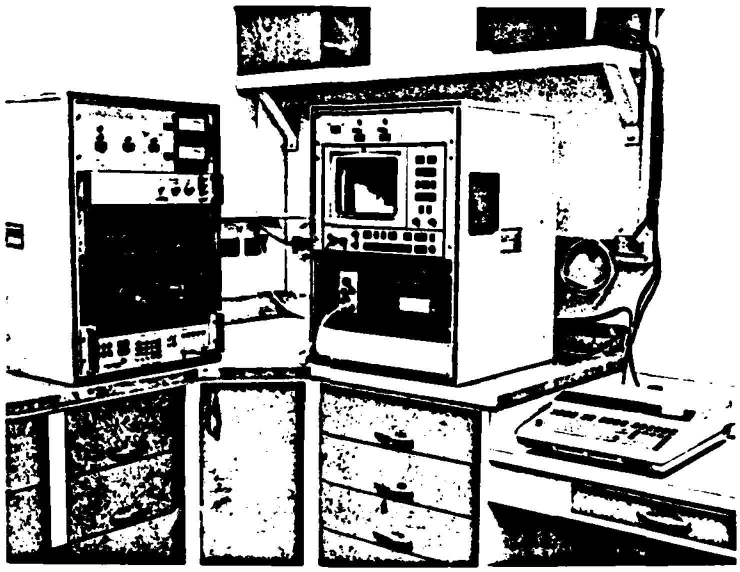


Fig. G4. Signal Generation Equipment (left), Measurement Apparatus (center) and Desk-Top Computer (right)

90 dB (re 20_ Pa) in each one-third octave band over the range of 100-5000 Hz.

Sound Level Measurements: The time and space averaged sound pressure levels in each room were measured using Bruel and Kjaer (B&K), 1 inch, the 4144 condenser microphones which were connected to a B&K type 2131 Digital Frequency Analyzer through a B&K type 2807 microphone power supply. The 2131 Analyzer was interfaced with a Hewlett Packard 9825A desk top computer which served to control the measurement sequence and to collect, reduce, and store all data required for the determination of the transmission loss values. The microphone power supply also functioned as a computer controlled switch to select back and forth between Source and Receiving room microphones. The microphones were rotated in a circular path with a diameter of 6 feet at a rate of about 4 RPM using a B&K type 3923 microphone booms. The locations of the microphone orbits were selected to provide a distance of at least one half wavelength between the microphone and nearest boundry or diffusing surface as required by section 9.3.1 of ASTM E90. In the case of wall test panels, the source room microphone boom was positioned on the floor of the room. In the case of roof/ceiling tests, the source room microphone boom was placed directly on the test roof. In all cases, the Receiving room microphone boom was placed on the laboratory floor.

In order to increase the effective signal to noise ratio of the 2131 analyzer, some measurements of source and receiving room sound pressure levels were measured with the dBA weighting network activated where necessary.

Measurement Sequence

Receiving Side Sound Absorption Measurement: The sound absorption in the receiving room, which is used in the calculation of the 10 log (S/A) term of the transmission loss formula (Equation G1) was determined prior to the measurement of room to room noise reduction. As an alternative, the computer program allows the use of absorption data determined via earlier tests if the operator considers the room conditions to be similar, thus allowing a considerable savings in test time.

Sound absorption is determined by introducing broad band random noise into the receiving room and then measuring the rate of decay in each one-third octave band after the sound is turned off. This is done by sampling the sound spectrum as measured by the B&K 2131 analyzer at 66 millisecond intervals and then computing a least squares equation of best fit to the resulting level vs. time history in each band. The sound absorption in each band is then computed using the Sabine equation as follows:

$$A = 0.9210 \, Vd/c \tag{G2}$$

where:

A = sound absorption. sabins
V = room volume, cubic feet
d = rate of decay, decibels per second
c = speed of sound, feet per second

The value of 10 log (S/A) is then computed for each 1/3 octave test frequency using the value of the test specimen area(s) input earlier in the program

The decay process is repeated ten times in order to provide an average value and the precision of the measurement of (10 log S/A). All absorption measurement functions are performed via computer control.

Noise Reduction Mesurements: The room to room noise reduction (NR) values were measured as follows:

With the source room sound spectrum adjusted to approximately 90 decibels, the B&K 2131 analyzer was set to obtain ten pairs of Source and Receiving room sound pressure levels. The sound pressure levels for a given pair represent a 16 second linear spatial average of the level in each room. The receiving side sound pressure levels were then corrected for any influence of background noise (as determined by separate earlier measurements). The difference in level for each pair of measurements were then determined to yield ten values of room to room noise reduction at each test frequency. Statistical data regarding the average values as well as the precision of the noise reduction measurements are also computed using these ten values of NR.

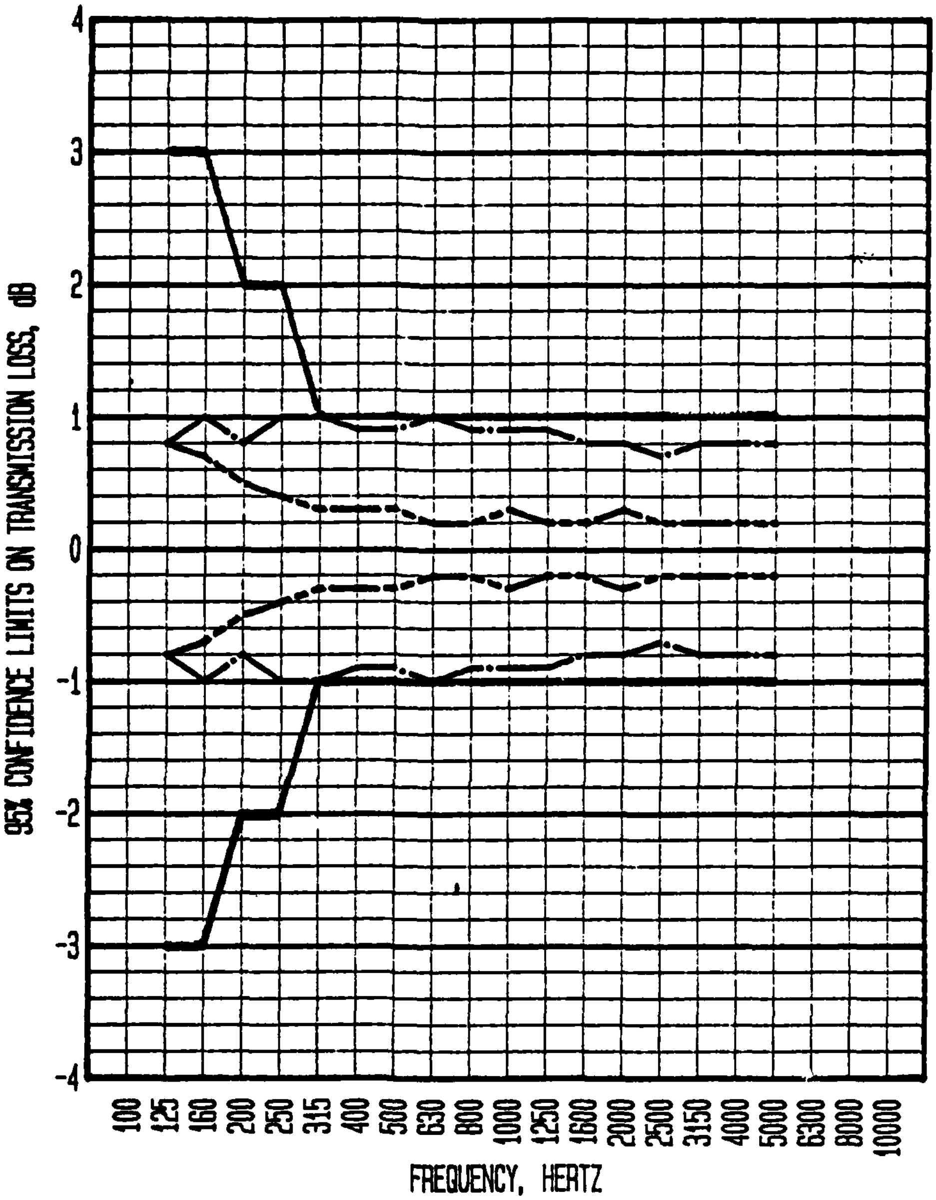


FIGURE G 5. 95% CONFIDENCE LIMITS ON TRANSMISSION LOSS

ASTM ALLOWABLE LIMITS
MAXIMUM TEST LIMITS MEASURED
TYPICAL TEST LIMITS MEASURED

In no case were measurements of receiving side sound level utilized where these values were less than 5 dB above the ambient or background sound levels.

Calculations and Measurement Precision

Sound Transmission Loss values in each one-third octave band were determined in accordance with equation (G1) using the time and space averaged values of NR and the averaged values of (10 log S/A) obtained as described above.

The precision of the TL measurements described in terms of the 95 percent confidence limits of the measured TL values were computed based on the following relationship.

$$\delta TL = (\delta^2 NR + \delta^2 (10 \log(S/A)))^{1/2} \qquad (G3)$$

Where:

δTL = 95% confidence limits on TL
δNR = 95% confidence limits on NR
$\delta (10 \log S/A)$ = 95% confidence limits on 10 log S/A

This expression is numerically equivalent to

$$\delta TL = (\delta^2 NR + \delta^2 (10 \log A))^{1/2} \qquad (G4)$$

as given in section 11.1 of ASTM E90 since the area S is assumed to be constant for a given test specimen (a reasonable assumption yielding $\delta^2 (10 \log S) = 0$).

ASTM E90 section 11.2 requires that the determinations of TL be made in such a way so as to ensure that the 95 percent confidence limits on TL be no greater than 3dB for bands centered on 125 and 160 Hz, 2dB for bands centered on 200 and 250 Hz and 1dB for bands centered from 315 to 4000 Hz. No measurement precision is stated at frequencies below 125 Hz or above 4000 Hz.

Measurements made under this project were well within these requirements and were in fact typically within _ 1 dB over the range of 100 to 5000 Hz. Figure G5 shows the ASTM required 95 precent confidence limits as a function of frequency, as well as the maximum and typical calculated values of 95 percent confidence limits for all measurements made under this program.

Corrections for Flanking Noise Effects

When the test specimen presents the only significant path for noise transmission from the source to the receiving room, the transmission loss can be calculated directly from the observed room to room noise reductions. If paths other than the specimen contribute significantly to the transmission of noise into the receiving room and they are not acounted for in the measurement or calculation procedure, the observed TL value will be lower than the true TL value due to the "flanking" of sound around the test sample. Due to the design of the test facilities. "flanking" is a concern only when testing the highest transmission loss constructions.

The ASTM E90 standard considers this effect by requiring that the sound power transmitted through the specimen be sufficiently greater than the sound power transmitted by the flanking paths to limit the influence of the flanking transmission on the observed TL to less than approximately 1/2 decibel.

When measuring the performance of panels of unknown transmission loss, it is necessary to compare the sound power observed to pass through the specimen with the sound power transmitted through the flanking paths alone in order to determine if flanking exists. It can be demonstrated that when this ratio is greater than 8.2 to 1., the influence of flanking on the observed TL will be less than 0.5 dB. (ASTM requires that this power ratio be 10 to 1 or greater. The use of the larger ratio offers an advantage in terms of convenience in calculations but provides a margin of error of 0.4 dB.)

The conditions under which this 8.2 to 1 ratio of transmitted powers occurs define a maximum specimen TL value which can be measured without exceeding the .5 dB error due to flanking. Figure G6 shows the computed maximum TL values for both walls and roof/ceilings.

In a few instances, the observed TL values exceeded these TL maximum, suggesting flanking influence. Corrections were applied by subtracting the flanking transmitted power from the total observed power transmission. In the case of the tests on wall panels, only two 1/3 octave data points for a single test (ref. test 82-047) were effected. Corrections for both values were limited to 2 dB or less.

In the case of the roof/ceiling assemblies, two potential flanking paths exist in the form of the facility separating panel and the specimen temporary supporting wall. As a result of the larger area exposed by these surfaces and the higher ratio of flanking to specimen transmitted sound power, these assemblies were more subject to flanking influences resulting in reduced values of "maximum measurable TL". In the majority of the tests performed, no corrections to observed TL values were required. Most of the roof/ceiling test corrections that were made were on the order of 1-3 decibels. In a very limited number of cases, the power transmitted by the specimen and flanking paths was found to be too close to make an accurate estimate of the true TL values. In these cases the flanking correction was limited to 3 decibels although the actual TL of the specimens are probably higher than the corrected values shown.

The corrections for flanking which were made involved, for the most part, the frequencies below 630 Hz. The only exception to this occured in three tests where a 1-2 dB correction wasa required at 5000 Hz.

Details of the approach taken to making the flanking corrections as well as the correction calculations themselves are included in Manville Laboratory Notebook Number 33.

Although the correction of TL data for flanking effects is not included in the E90 procedure, the basis for these corrections is well founded and the accuracy of the corrected TL results is felt to be well within the allowable experimental error of the measurements.

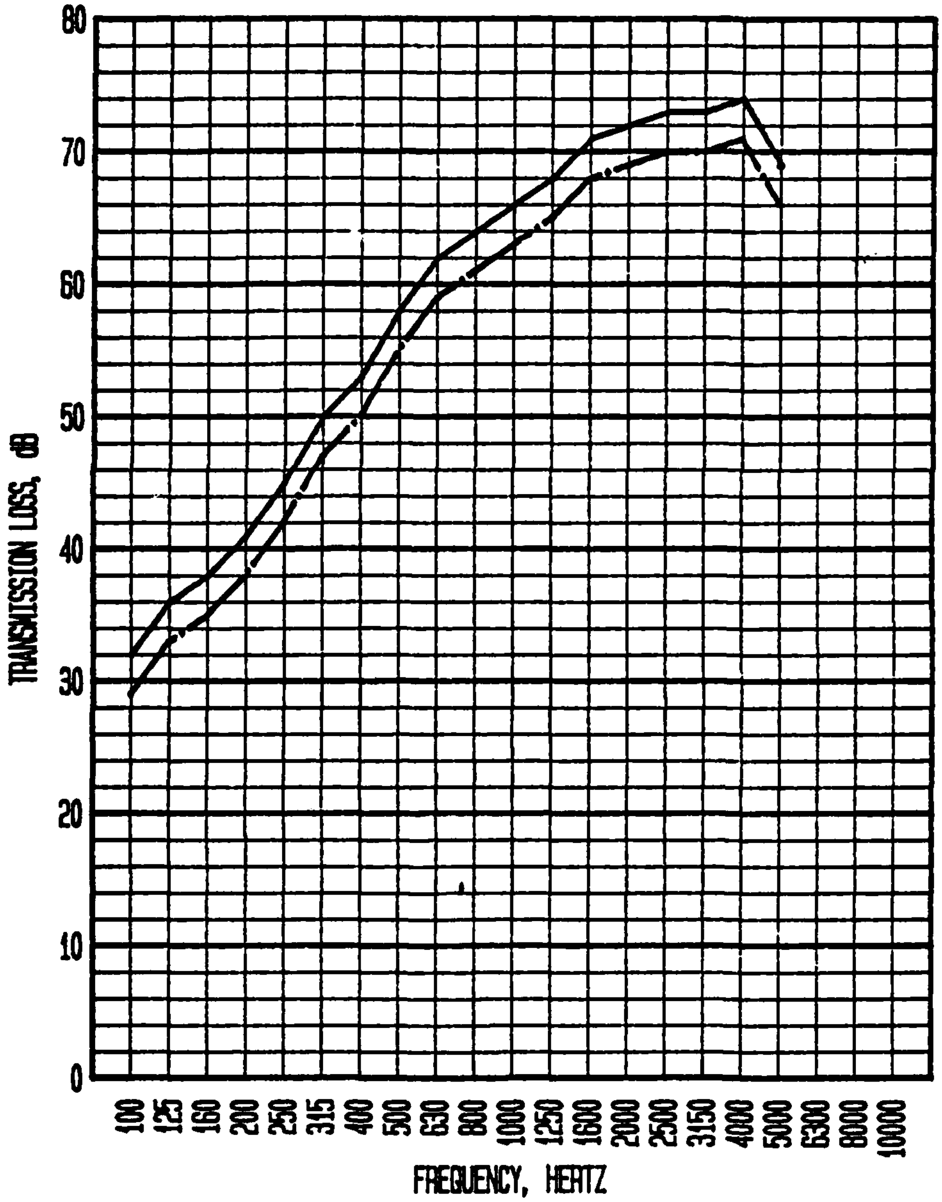


FIGURE G 6. MAXIMUM APPARENT TL WHICH CAN BE MEASURED WITH LESS THAN 0.5 dB INFLUENCE DUE TO FLANKING

WALL TEST SPECIMENS

ROOF-CEILING TEST SPECIMENS

Figure G7a

Typical Computer Input Output For Transmission Loss Test

	Transmission Loss Test Test nbr - 82053
Test date and time (5/12/82, 7:55 AM)	Date 820512.0755
* Panel and construction identification 5 lines available	PANEL "2" ORIGINAL CONSTR. CAULKED INTER. & EXTER
* Specimen area radiating into receiving room required for 10 log S/A correction	Test area 126 SF
* Temperature, barometric pressure and relative humidity at time of test	Rec'v room: Temp 75 F Press 616 mmHg R.H. 26 %RH
Difference in microphone calibrations and date of cal. (GR refers to green coded microphone as used in source room being higher than receiving room microphone by +1.0dB.	Mike calibration GR 1.0 Date 820512.0734

Sound absorption test results showing date of determination
Column 1 = Frequency
Column 2 = Avg. 10 log S/A correction based on determination of A
Column 3 = 95% confidence limits for 10 log S/A (Required to calculate 95% confidence limit on TL)

Absorption Test
Date 820512.0757

Area/Absorb Cor.

Freq	Avg	95%CL
100	1.1	0.1
125	1.4	0.2
160	1.2	0.2
200	1.3	0.2
250	1.0	0.2
315	1.4	0.1
400	1.3	0.1
500	1.3	0.1
630	1.3	0.1
800	[illegible]	0.1
1000	1.1	[illegible]
1250	[illegible]	0.1
[illegible]	0.1	0.1
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
3150	[illegible]	[illegible]
4000	-2.7	[illegible]
[illegible]	[illegible]	[illegible]

* Data input manually by operator.

Cont'd on Figure 7b

Figure G7b

Typical Computer Input/Output For Transmission Loss Test

(Cont'd from Figure G7a)

Results of background (Ambient Noise) determinations which are used to correct receiving room levels for influence of ambient noise levels

Bkgrd noise Freq	Level
100	17.4
125	27.1
160	22.5
200	26.9
250	21.4
315	21.4
400	15.6
500	12.9
630	13.0
800	15.0
1000	11.9
1250	9.7
1600	9.7
2000	10.2
2500	11.2
3150	11.5
4000	9.7
5000	7.9

TEST RESULTS:

STC = Sound transmission class single number rating based on individual TL values over frequency range of 125 - 4000 Hz. (Criteria for STC determinations = sum of deviations)

STC class 46
(sum of dev) 27

Column 1 = 1/3 octave band center frequency, Hz

Column 2 = Computed sound transmission loss, dB

Column 3 = Value of the standardized STC reference contour in dB when contour is fitted to measured TL values within criteria of ASTM E-413

Column 4 = 95% confidence limit on measured transmission loss values (dB)

Freq -Hz	TL	STC	95% conf
100	31	0	0.4
125	33	30	0.4
160	32	33	0.4
200	34	36	0.4
250	37	39	0.4
315	39	42	0.3
400	40	45	0.3
500	43	46	0.2
630	45	47	0.2
800	46	48	0.2
1000	47	49	[illegible]
1250	49	50	0.1
1600	49	50	0.1
2000	45	50	0.1
2500	48	50	0.1
3150	51	50	[illegible]
4000	53	50	[illegible]
5000	55	0	[illegible]

APPENDIX H

AIR INFILTRATION TEST PROCEDURE

APPENDIX H

Air Infiltration Test Procedure

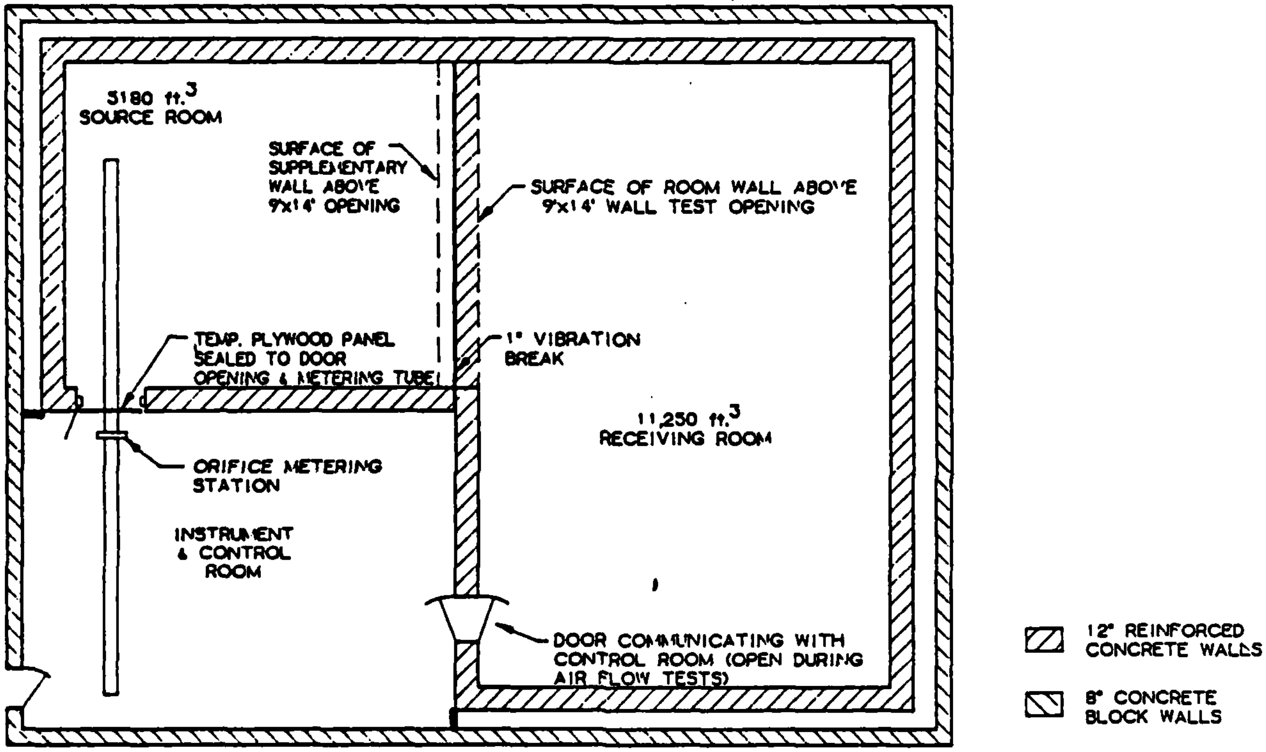
The rate of air flow through the test specimens was determined in accordance with ASTM "Standard Test Method for Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors" designation E283-73*, with the exception noted in the accuracy section of this appendix (Figure H5). The measurements were made within the Manville R&D Center Acoustical Labortory test chambers utilizing the same specimens that were installed and tested for sound transmission loss. The source room (reference Figure H1) served as a sealed chamber which was either pressurized or partially evacuated in order to develop a pressure difference across the specimen and thus induce air infiltration through the panel. In all cases the exterior surface of the specimen faced the source room while the interior surface was exposed to the acoustical laboratory receiving room.

Flow rates were measured using a metering station consisting of a square edged orifice which was inserted in a length of smooth plastic pipe between a fan driven air pump and the sealed room as shown in Figures H1 and H2.

The pump consisted of an industrial duty vacuum cleaner which could be connected to either blow air into the source room and thus pressurize it (cause infiltration) or to draw air out of the room (cause exfiltration). The resulting flow of air through the metering station caused a pressure drop across the orifice which was proportional to the square of the flow rate. The speed of the vacuum cleaner motor could be precisely adjusted using a variable ratio transformer, in order to vary the rate of flow through the specimen thus controlling the static pressure difference across the panel.

---

* "Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors", E283-73, Vol. 18, American Society for Testing and Materials, Philadelphia, Pa. 1973.



PLAN VIEW OF TEST CHAMBERS

FIGURE H1
3/16 IN. = 1FT.

C1853

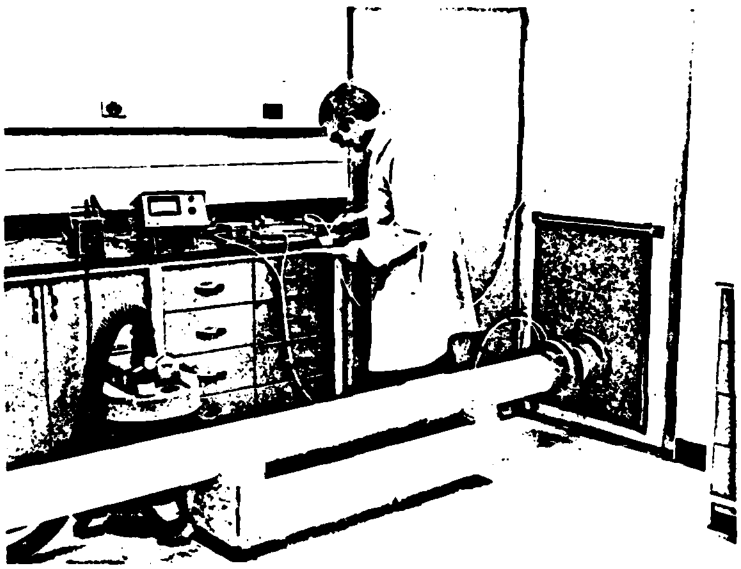


Fig. H2. Pressure/Vacuum Source Connected to Orifice Transition Section (white tube) and Electronic Pressure Differential Apparatus (on bench) Connected to Orifice Measurement Section (right).

Two interchangeable orifice plates with bore diameters of 1.238 and 2.475 inches were obtained from Daniel Industries Inc. in order to cover the anticipated infiltration rate range.

The metering section consisted of two twelve foot lengths of nominal 6 inch, PVC plastic pipe which were joined using PVC plastic flanges. A given orifice plate was mounted by placing it between the flanges with 1/16 inch neoprene rubber gaskets used on either side of the plate. The flanges were drilled and tapped for pressure taps in accordance with Daniels Industries Inc. specifictions.

The metering section pipe lengths of twelve feet (24 pipe diameters) were selected in accordance with good engineering practice in order to assure smooth approach and exit conditions on either side of the orifice plate.

One end of the metering section was equipped with a PVC plastic cap which was machined to allow the connection of the air pump in either the pressurization or evacuation mode. The opposite end of the metering section passed through and was sealed to a plywood panel which was mounted in the access door leading to the source room (reference Figures H1 and H2).

The flow pressure differential across the orifice was measured using a Datametrics Barocel electronic manometer system consisting of a Model 1173 analog meter and a Model 570D pressure transducer with a full scale range of 1.0 inch H_2O. The reported accuracy of the manometer is ±.01 percent.

The room static pressure was measured using a Dwyer Model 171 inclined manometer with a range of 1 to 2.5 inch H_2O which was modified to measure to 0.3 inch H_2O. The reported accuracy of the inclined manometer is ±2 percent of full-scale or ±0.006 inch H_2O. The manometer sensed the Source room static pressure through a length of polythylene tubing which passed through the plywood panel installed in the access door opening. The open end of the tube extended three feet beyond the door and was positioned three feet above the floor as shown in Figure H1.

Both positive and negative pressures over the range of 0.1 to 0.3 inch H_2O were imposed on the test panel exterior

surface with flow determination made at five equally spaced points over the positive and negative ranges. The upper value of 0.3 inch H_2O was selected in order to comply with ASTM E-283 requirements.

The calculation of flow rate for each static pressure setting for a given mode of operation (pressure or vacuum) was accomplished via a computer program which had been written specifically for use in this project.

Data input into the program included the following:

1. Sample identification

2. Test date and time

3. Pressure orientation (Pressure or vacuum on panel exterior)

4. Flowing temperature

5. Barometric pressure

6. Orifice bore

7. Five sets of static pressure and orifice differential pressures

Based on these inputs, the program calculated the flowing rate in cubic feet per minute corrected to the standard conditions (SCFM) specified in section 6.2 of ASTM C283 as follows:

Pressure:	29.92 inch Hg
Temperature:	69.4°F
Air Density:	0.075 lb/ft

In all cases throughout this report references to flow rates in SCFM refer to measurements corrected to the above conditions.

The measured static pressure and flow rates were transformed to logarithmic values and a linear regression was performed on the transformed data to provide an equation defining the least squares line of best fit. Values of flow rate at exact static pressures of from 0.05 to 0.3 inch H_2O in increments of exactly 0.05 inch H_2O

Figure H3a

Typical Computer Input/Output For Air Flow Test

* Test Specimen Identification (5 lines available)	DATA FOR CONST: PANEL "E" INTER. & EXTER. CAULKED ----------------
Test Date	Date: 05/18/82
Test Time	Time: N/B #32ir.
Input for pressure or vacuum on panel exterior	Vacuum on Ext.
Barometric pressure and temperature base to which measured flows are correctd in order to obtain CFM under standard conditions (SCFM)	Pressure base: 29.92 Inches Hg Temp. Base: 69.4 deg F
* Temperature and barometric pressure at time of test	Flowing Temp.: deg F=73.0 Barom. Pressure: Inches Hg=24.33
* Orifice used for measurements	Orifice Bore: Inches=1.238
Flowrates (corrected to SCFM) for observed room gage pressure in inches H_2O	FLOW DATA: ----------------

Static Pressure (Inches)	Flow Rate (SCFM)
-0.298	7.4
-0.236	6.3
-0.171	5.0
-0.127	3.9
-0.100	3.3

*Data input manually by operator.

Cont'd on Figure H3b

Figure H3b

Typical Computer Input/Output For Air Flow Test

(Continued from Figure H3a)

PRESSURE DATA:

* Observed room static pressure values in inches H_2O and observed orifice plate pressure differential in inches H_2O. These data are input immediately after the entry of the orifice bore but are not printed until the corrected flow volumes are calculated and the output printed.

Static Pres. (Inches)	Orif. Pres (Inches)
-0.298	0.165
-0.236	0.116
-0.179	0.076
-0.127	0.046
-0.100	0.033

Flowing pressure on upstream side of orifice based on room static pressure (used in calculation of orifice flow coefficient)

Static Pres. (Inches)	Flowing Pres. (psia)
-0.298	11.941
-0.236	11.943
-0.179	11.945
-0.127	11.947
-0.100	11.948

FLOW COEF:

Orifice flow coefficient computed based on factors described in Daniels Industries flow calculation data sheet

Static Pressure Inches	C Prime Factor
-0.298	5.291478
-0.236	5.291476
-0.179	5.29147[illegible]
-0.127	5.2914[illegible]
-0.100	5.29148[illegible]

Continued on Figure H3c

Figure H3c

Typical Computer Input/Output For Air Flow Test

(Continued from Figure H3b)

Regression equation constant and coefficient (slope) based on least squares line of best fit to logarithmically transformed room pressure-SCFM data sets

```
   LEAST  SQUARES
      ANALYSIS
-----------------
To be plotted on
log-log paper.

   Q = mx+b

 Where :
  Q=log SCFM
  m=Slope
  b=log Intcpt
  x=log static
    pressure

Slope =      0.74

Log Intcpt= 1.2[illegible]
```

Flow rates in SCFM for room pressures in exact increments of 0.05 inch H_2O based on regression equation.

```
Estimated Flows
at .05 inch H2O
Static  Pressure
Increments:


Static        Flow
Pressure      Rate
(Inches)     (SCFM)
-----------------
-0.050        2.0
-0.100        3.3
-0.150        4.5
-0.200        5.5
-0.250        [illegible]
-0.300        7.[illegible]
```

were then computed based on the regression equation. These computed values of flow are the data which have been used in this report.

A typical computer print out is shown in Figure H3 along with a description of the various inputs and calculated values.

The flow as measured for a given specimen includes the flow through the test panel itself as well as the extraneous leakage through the facility due to small cracks in the junctions of the room walls, floors, ceilings, etc.

In order to determine the net leakage through the test specimens, it was necessary to measure and subtract the value of the extraneous or facility leakage.

The facility leakage was determined by covering the test panel area with polyethylene sheet and measuring the total infiltration rate over the static pressure range of -0.3 to +0.3 inch H^2O. Leakage measurements were made for each of the three wall test panels with corrections applied to the data for the appropriate specimens. In the case of the roof/ceiling test panels, facility leakage measurements were made for panel D only. This was done with plastic film applied over both sides of the roof/ceiling structure and over both sides of the supporting wall within the source room. After the determination of the facility leakage was accomplished, the plastic sheet was removed from the test specimen but was left in place on the supporting wall for the remainder of the test. The facility leakage rates as determined were applied to the total flow measurements made for both roof/ceiling test designs in order to determine the net roof/ceiling test panel leakage.

Measurement Accuracy

The accuracy of the total flow rate (specimen air infiltration plus facility leakage) is a function of the total flow rate through the metering section.

Daniel Industries states that the orifice plates used in this program provide accuracies of ±1 percent for orifice Reynolds number of greater than 25,000. This equates to flow rates of 25 cfm and higher for the 1.238 inch orifice and greater than 60 cfm for the 2.475 inch orifice as used in the program. Daniel Industries does not provide reliable figures of accuracy below their flow rates. As a result, it became necessary to establish the orifice calibrations in-house in order to establish the accuracy of measurements made below 25 and 60 cfm with each respective plate.

This was accomplished by measuring the flow through the metering section with a Singer Model DTM-325 precision dry test gas meter. The results of these measurement demonstrate accuracies within 1 percent for total flow rates of 7 SCFM and above for the 1.238 inch orifice. At flow rates between 7 and 4 SCFM the accuracy was found to be between 1-1/2 and 3-1/2 percent or approximately 0.1 SCFM expressed in terms of volumetric flow rate units.

The accuracy of the 2.475 inch orifice plate was found to be between 4 and 5 percent in the range of 5 SCFM. (The upper measurement limit of the dry test meter measurements below 5 SCFM demonstrated rapid degradation in accuracy to about 8 percent at 2.5 SCFM. This relationship suggests an accuracy of about 2 percent (±0.2 SCFM) at the lowest value of flows measured with this plate during the program (11-12 SCFM) improving to an accuracy of 1 percent at flows of well below 60 SCFM.

The air infiltration rate for a test specimen alone is the total mesured flow minus the flow due to facility leakage. As a result, the accuracy of the difference in these two numbers is influenced by the accuracy of each of the individual measurements.

The uncertainty of an infiltration rate can be expressed mathematically as follows:

$$\delta Q = (\delta Q_m{}^2 + \delta Q_1{}^2)^{1/2} \qquad \text{(H1)}$$

where:

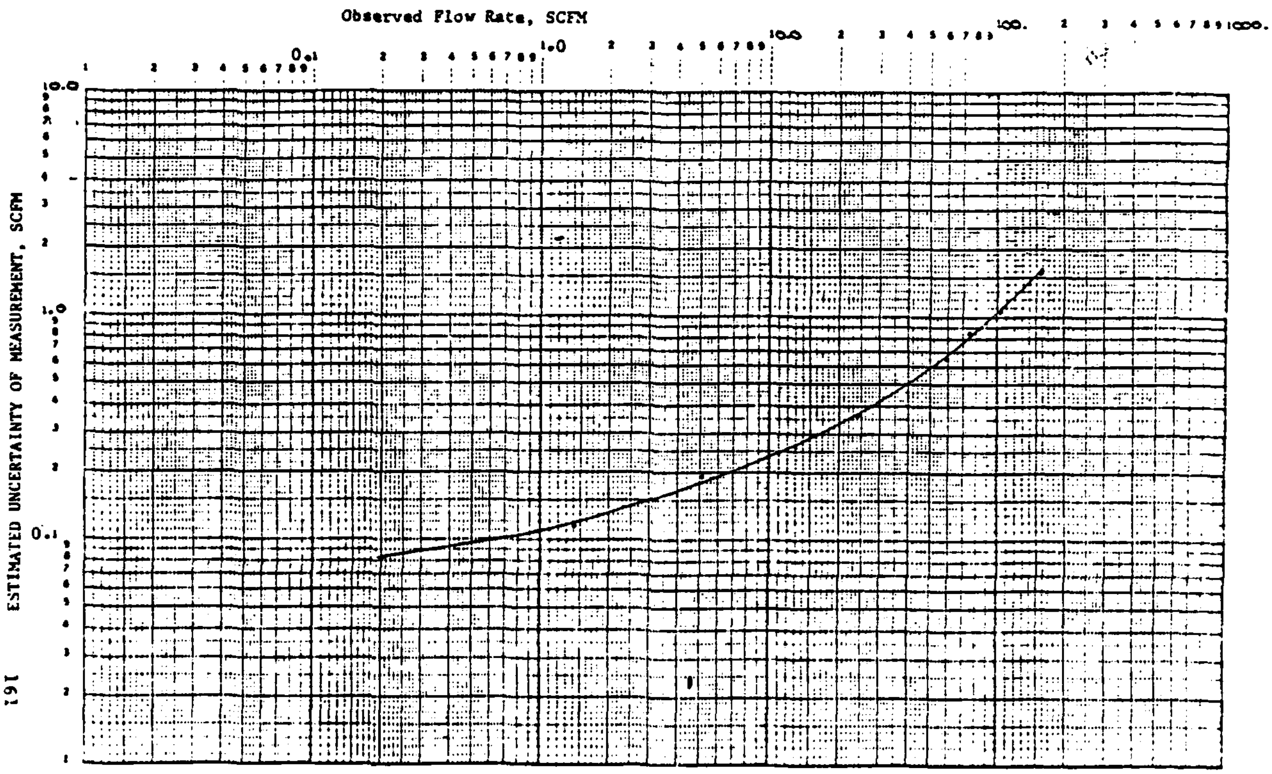


Fig. H4: Estimated uncertainty of air flow measurements as a function of the observed flow rate.

δQ = uncertainty of the specimen infiltration rate, SCFM
δQ_m = uncertainty of total metered flow, SCFM
δQ_l = uncertainty of facility leakage flow, SCFM

Figure H4 shows a plot of estimated uncertainties or errors in units of SCFM as a function of the specimen infiltration rate. This relationship is based on uncertainties calculated in accordance with Equation H1 for eight specimens tested under this program and is felt to be representative of the errors associated with all infiltration rates reported herein.

It will be noted that when expressed as a percentage, the errors at very low infiltration rates (less than about 3 SCFM) exceed the ASTM E-283 maximum allowable value of 5 percent in spite of the fact that the total flow and leakage flow rates are each made at accuracies of better than 3-1/2 percent. This is due to the fact that the error in SCFM rapidly approaches the measured differences at low infiltration rates.

This in no way reduces the significance of the small number of measurements falling into this category however as the intent of the program has been to identify the direction and magnitude of <u>changes</u> in performance. In this respect, it is the difference in performance for retrofits of a given base assembly which must be considered. While the accuracy of a given infiltration rate is subject to errors in both the total flow and facility leakage flow measurements, the differences in performance for retrofits over the performance of the base assembly are comparable in terms of the accuracy of the total flow rate for the individual retrofit. As noted above, these accuracies have been found to be within about 1 percent or 0.1 SCFM in the range where the E-283 criteria of 5 percent accuracy on the <u>specimen</u> flow is not met. This means that for specimen infiltration rates of 3 SCFM and below, differences in performance for retrofits of a given basewall assembly as small as 0.2 SCFM (the sum of the maximum expected errors) can be considered to be significant.

APPENDIX I

THERMAL CONDUCTANCE TEST PROCEDURE

APPENDIX I

Thermal Conductance Test Procedure

The thermal transmittance properties of most of the constructions evaluated in this investigation were determined by calculations performed in accordance with the procedures outlined in Chapter 23 of the 1981 ASHRAE Handbook of Fundamentals.* Because of the complex nature of the heat flow paths in two of the retrofit constructions, actual thermal conductance tests were conducted on the two base constructions and respective retrofits on each.

Thermal conductances tests were performed in accordance with the requirements of ASTM-C236, Standard Test Method for the Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box.** The test apparatus utilized is accredited under the U. S. Department of Commerce National Voluntary Laboratory Accreditation Program (NVLAP) for thermal tests.

The test apparatus requires specimens 64 by 80 inches overall, with a heat flow metered area 32 by 48 inches. Tests were conducted under winter conditions with the exterior or cold side air temperature controlled at approximately 18°F. The interior or warm side air temprature was maintained at about 72°F. Tests on the wall specimen were conducted with the specimen oriented vertically, with horizontal heat flow. For the roof/ceiling specimen, it was oriented horizontally with heat flow upward (winter).

---

* ASHRAE Handbook of Fundamentals, Chapter 23, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, Ga., 1981.

** "Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box", C236-80, Vol. 18, American Society for Testing and Materials, Philadelphia, Pa. 1980.

Copper-constantan thermocouples were used to measure temperatures including:

Hot air
Hot surface (of test panel)
Cold surface (of test panel)
Cold air
Hot air (guard)
Hot surface (guard)
Metering box (balance)

All data were recorded at one-hour intervals by a computer data-logger, which then converted millivolts to equivalent temperatures and calculated the average temperature and standard deviation for each group of thermocouples.

Constant temperature conditions were controlled at three separate areas within the test apparatus: hot side metering area, guard-to-metering area balance, and cold side. In each case temperature regulation was achieved by a controller supervising a continuously variable DC power supply connected to a resistance heater. DC power was utilized because of the close temperature control action possible with this system, and the ability to monitor power used accurately with the same data-logger used for temperature measurement. The refrigeration system for the cold side was operated continuously. Temperature control was achieved by an electric reheater to that desired.

Power input to the metering area consisted of that to the air circulation fans and to the resistance heater. Each power was determined separately by measuring the voltage drop across precision resistors connected for potential and for current. In addition, a correction was made for the small guard to metering area temperature unbalance.

The whole guarded hot box test procedure is under computer supervision. After a test specimen has been installed, initial settings are made to the temperature controls and power inputs. At intervals of one hour, temperature and power data area taken, averaged and stored in the computer. When apparent steady-state heat flow conditions have been established, data accumulation is continued for four 1-hour periods and the average thermal performance of the test specimen calculated. Data is accumulated at one-hour intervals for a second succeeding four hour period,

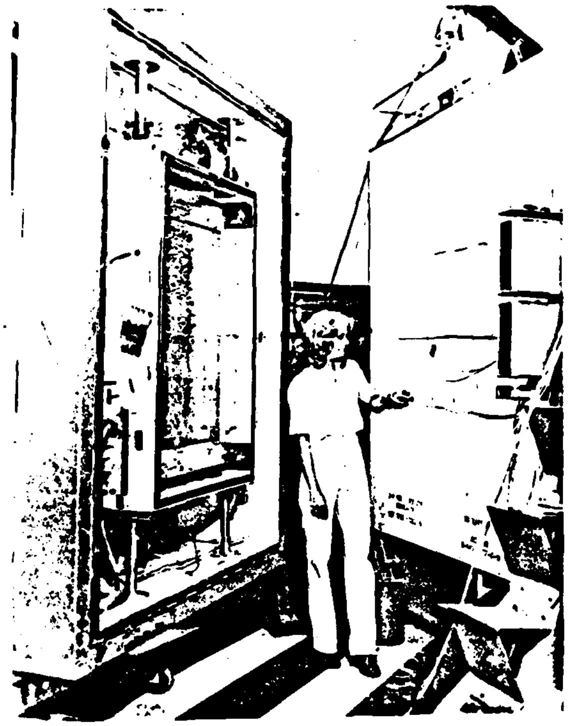


Fig. I1. Guarded Hot Box Test Apparatus Showing Interior.

Fig. I2. Guarded Hot Box with Control Panel.

and the average thermal performance again calculated. If the results of the two test periods agree within one percent, and there is no evidence of a long term temperature drift, the requirements of Section 8.2 of ASTM-C236 are satisfied and the test is completed.

Figure I1 shows the interior of the guarded hot box apparatus. The wall test specimen is on the right. The hot side assembly is on the left, showing the central metering box area surrounded by the guard area. Figure I2 shows the assembled test apparatus on the left, with the control panel on the right. A typical data printout for a completed test is shown in Figure I3.

DAY	TIME	HOT SIDE (AVG/SD)		HOT SIDE GUARD (AVG/SD)		COLD SIDE (AVG/SD)		HEATER E(MV)	HEATER I(MV)	BALANCE	HOT AIR (AVG/SD)		HOT AIR GUARD (AVG/SD)		COLD AIR (AVG/SD)		FAN E(MV)	FAN I(MV)
134	0: 9: 6	68.7	1.4	68.4	.4	21.1	1.6	41.674	4.890	.002	72.8	.2	72.7	.1	19.9	.5	11.602	3.030
134	1: 9: 3	68.6	1.4	68.4	.3	21.3	1.7	41.668	4.910	-.001	72.9	.2	72.7	.1	20.1	.7	11.610	3.030
134	2: 9: 0	68.8	1.3	68.4	.4	21.5	1.7	41.660	4.890	-.003	72.8	.2	72.7	.1	20.2	.6	11.620	3.040
134	3: 8:57	68.9	1.3	68.5	.4	21.9	1.6	41.756	4.890	-.003	72.8	.2	72.6	.1	20.8	.6	11.604	[illegible]
AVERAGES (4)		68.8		68.4		21.4		41.690	4.895	-.001	72.8		72.7		20.2		11.609	[illegible]
STD DEV (4)		.1		.0		.3		.045	.010	.002	.0		.0		.4		.008	.010
134	4: 8:54	68.9	1.3	68.5	.3	22.9	1.5	41.558	4.850	-.004	72.8	.2	72.6	.1	21.9	.7	11.602	3.040
134	5: 8:50	68.8	1.3	68.5	.4	22.6	1.6	40.830	4.780	-.004	72.9	.2	72.7	.1	21.5	.7	11.608	3.040
134	6: 8:47	68.9	1.3	68.5	.4	22.0	1.7	41.054	4.820	-.006	72.8	.2	72.7	.1	20.7	.7	11.606	3.030
134	7: 8:44	68.8	1.3	68.5	.3	21.6	1.8	41.100	4.810	-.005	72.8	.2	72.6	.1	20.3	.7	11.652	3.070
AVERAGES (4)		68.9		68.5		22.3		41.136	4.815	-.005	72.8		72.7		21.1		11.617	3.045
STD DEV (4)		.0		.0		.6		.305	.029	.001	.0		.0		.7		.023	.017
AVERAGES (8)		68.8		68.4		21.9		41.412	4.855	-.003	72.8		72.7		20.7		11.613	3.041
STD DEV (8)		.1		.0		.6		.358	.047	.003	.0		.0		.7		.017	.014

DAY	TIME	POWER HTR	POWER FAN	POWER TOTAL	HEAT FLOW	U VALUE	R VALUE	C VALUE	MEAN TEMPS W/AIR	MEAN TEMPS PANEL	SURF AIR COEFFS IN	SURF AIR COEFFS OUT
134	0: 9: 6	18.661	3.379	22.040	6.844	.1293	6.9648	.1436	46.4	44.9	1.676	5.066
134	1: 9: 3	18.742	3.381	22.123	6.862	.1301	6.9201	.1445	46.5	45.0	1.680	5.881
134	2: 9: 0	18.655	3.396	22.051	6.834	.1298	6.9209	.1445	46.5	45.1	1.694	5.257
134	3: 8:57	18.694	3.403	22.097	6.849	.1316	6.8627	.1457	46.8	45.4	1.719	6.421
AVERAGES (4)		18.688	3.390	22.077	6.847	.1302	6.9171	.1446	46.5	45.1	1.693	5.856
STD DEV (4)		.040	.011	.039	.011	.0010	.0419	.0009	.2	.2	.019	.475
134	4: 8:54	18.447	3.391	21.838	6.766	.1328	6.8013	.1470	47.4	45.9	1.706	7.122
134	5: 8:50	17.868	3.392	21.260	6.587	.1281	7.0143	.1426	47.2	45.7	1.640	5.566
134	6: 8:47	18.121	3.380	21.501	6.656	.1276	7.0408	.1420	46.8	45.4	1.671	5.056
134	7: 8:44	18.098	3.439	21.538	6.670	.1269	7.0787	.1413	46.6	45.2	1.661	5.066
AVERAGES (4)		18.134	3.401	21.534	6.670	.1289	6.9838	.1432	47.0	45.6	1.669	5.702
STD DEV (4)		.238	.027	.237	.074	.0027	.1245	.0026	.4	.3	.028	.976
AVERAGES (8)		18.411	3.395	21.806	6.758	.1295	6.9505	.1439	46.8	45.3	1.681	5.779
STD DEV (8)		.336	.020	.330	.107	.0020	.0931	.0019	.4	.3	.025	.715

Figure I3. Typical computer printout of guarded hot box text results.

APPENDIX J

RETROFIT MEASURES TO CONTROL NOISE FROM EXTERIOR SOURCES IN FAMILY HOUSING UNITS

APPENDIX J

Retrofit Measures to Control Noise from Exterior Sources in Family Housing Units

This section was written with the Navy base facilities engineer in mind. The purpose is to provide him with a general background on the effectiveness of retrofit measures to control the amount of exterior noise transmitted through the envelope of family housing units, especially noise resulting from aircraft operations. It is not expected that this will make him an experienced acoustician. However, it should give him an insight in which control measures might be worth pursuing further.

Noise - Noise has been described as unwanted sound. In the measurement of noise or sound levels, there are two criteria of concern: sound intensity and frequency distribution.

Sound intensity is measured in decibels (dB). The decibel scale is logarithmic, and was selected because it approximates the response of the human ear to sound. However, because it is logarithmic, simple arithmetic does not follow when adding or subtbacting. The following table on subjective effect of changes in sound characteristics was taken from a text by Xerges*, and illustrates the point. This text incidently is an excellent information source for the novice in acoustics, since the author has translated technical terms and concepts into language more meaningful to everyone.

* L. F. Xerges, "Sound, Noise and Vibration Control", 2nd Edition, VanNostrand Reinhold, 1978

Subjective Effect of Changes in Sound Characteristics

Change in Energy Level	Change in Sound Level	Change in Apparent Loudness
26 Percent	1 dB	Insignificant
Doubling	3 dB	Just perceptible
Tripling	5 dB	Clearly noticeable
Ten Times	10 dB	Twice (or 1/2) as loud
100 Times	20 dB	Much louder (or quieter)

As noted above, reducing the sound intensity to half its value, produces a "just perceptible" change in apparent loudness. The sound intensity must be reduced to one-third, in order to effect a "clearly noticeable" change. In order to achieve an apparent change of "one-half" in loudness, the sound intensity must be reduced to one-tenth its previous value. Understanding of these considerations is very important before undertaking any noise control measures.

The second criteria or characteristic of sound is its frequency distribution. Different sounds have different qualities, or different spectral distributions of sound energy throughout the frequency range. For example, jet aircraft generated noise is "heavy" in the low frequency end of the spectrum during "run-up" and "take off". During landing operations, there is a dominance of high frequency noise.

The human ear has the capability of responding to sounds ranging in frequency from 16 to 20,000 cycles per second (cps) or Hertz (Hz), with a decrease in response to high frequency sound with age. The ear has greater sensitivity to sounds in the range of 500 to 5000 Hz than to lower or higher frequencies.

For acoustical measurements, the frequency spectrum is commonly divided into one-third octave bands. An octave is a doubling of frequency, i.e., 1000 Hz versus 2000 Hz.

Thus, the one-third octave bands are: 100, 125, 160, 200, 250, 315, 400 Hz, etc. We will be concerned with sounds in the 100 to 5000 Hz range.

Sound Transmission - In the transmission of sound from one point to another, three factors are involved: source, path and receiver.

As regards to aircraft generated noise, much has been done to reduce the noise problem by modifications to the jet engine which reduce the noise emitted at the source. However, source is still a concern because of the differences in frequency distribution with different aircraft and different operations.

Concern for path involves many considerations. Since sound intensity is attenuated or reduced with distance, distance is a factor. The nature of the path is also a factor, since terrain such as hills and berms can act as a barrier. On the other hand, adjacent buildings can intensify the sound by providing sound reflecting surfaces.

Our concern in this investigation is the modifications to that portion of the sound path provided by the exterior envelope of a residential building.

While our present concern is with the building envelope, the role of the receiver should not be lost. The sound intensity in the receiving room will be higher, all other factors being equal, if the room is highly reverberent, with little sound absorbing material present. The sound transmitted through the envelope is reflected off the interior surfaces, and in effect is "heard" many times over. On the other hand a "dead" room, with ample sound absorptive surfaces, will prevent multiple reflections, and thereby provide a lower sound intensity level.

The sound transmission properties of a barrier are determined by measuring the difference in sound intensity on the two sides of the barrier. The sound intensity on the source side (expressed in decibels) minus that on the receiving side is a measure of the effectiveness of that barrier in preventing or attenuating the passage of sound through the barrier. Since the sound level attenuation is expressed in decibels, the same considerations of a

logarithmic scale apply. Thus, a partition which permitted only one-half the sound energy to pass through it would have a +3 dB rating over the reference partition.

The overall sound barrier performance of building partitions is customarily expressed in Sound Transmission Class (STC) units. The higher the STC rating of a barrier, the better it is at attenuating the passage of sound. STC units were developed originally for rating interior partitions as to their human speech isolation capability. When applied to other noise sources, such as aircraft generated, the application of STC ratings can be questioned. However, STC values are generally understood by building professionals, and therefore, are useful.

The following table was taken from Xerges, and represents what he considers good practice for the walls of various types of residential occupancies.

Generally Recommended Sound Transmission Class Values

for Exterior Walls

Occupancy	STC
Single family residence - bedroom	35-39
Single family residence - living room	35-39
Apartments - bedroom	40-44
Apartments - living room	35-39
Motel and urban hotel - bedroom *	40-44
Motel and urban hotel - bedroom **	45-49
Motel and urban hotel - bedroom ***	45-49

* Normal street or highway noise
** Heavy highway noise
*** Airport noise

Noise Transmission Control - This investigation was aimed at determining the acoustical benefits to be derived from taking certain energy conservation retrofit measures which reduce air leakage and increase thermal insulation level. The purpose was to quantify the improvement in acoustical isolation of various Navy Family Housing structures. Three typical base walls and two base roof/ceilings were investigated. The results confirmed that air leakage control and added insulation can indeed reduce both thermal energy losses and noise transmission. The findings may be summarized as follows:

1. In family housing units, to improve acoustic isolation from exterior noise, the most important sound transmission path should be attacked first. Generally windows are the weakest link acoustically in the building envelope.

2. Retrofit measures which attack secondary level noise leaks in the building envelope, will not provide noticeable improvement in the interior noise level.

3. The acoustical performance of the two roof/ceiling constructions tested was superior to that of the three wall contructions. Thus roof/ceiling constructions should not be retrofitted for acoustical purposes until after the wall performance has been improved.

4. Caulking and sealing of the exterior envelope can improve sound isolation and reduce air leakage.

5. If contract labor rates are used for installation of acrylic latex caulking estimated to be $1.10/linear foot for labor, materials and contractor markup, the benefit-to-cost analysis makes the caulking retrofit of doubtful desirability; if installed by the owner at an estimated $0.06/linear foot material only cost, the retrofit is very desirable.

6. Caulking and sealing of exterior walls can be accomplished by sealing either the exterior or interior surface; the choice of exterior or interior depends on accessibility and cost. Only a slight improvement was found when walls were completely sealed on both surfaces.

7. If windows must be opened for ventilation and/or cooling, no amount of sound isolation improvement to the wall or roof/ceiling will provide any overall reduction of the interior noise levels in areas where the exterior noise level is high.

8. A commercial combination storm window, added to a prime window, improves sound isolation and reduces thermal conductance. It may not reduce air leakage through the window assembly if drains for rain water are a part of the design.

9. Installation of an extra heavy storm window (1/4 inch thick glazing) provided a marked improvement in the acoustical performance of the window.

10. Replacing a single glazed steel casement style sash with an aluminum double-glazed thermal break replacement type sash was very effective in reducing air leakage, sound transmission and thermal conductance.

11. Adding an insulated suspended ceiling provided a marked reduction in both sound transmission and thermal conductance.

12. Acoustically treating a crawl space area also provided improvement by greater sound isolation and reduced thermal conductance.

13. Acoustical treatment of an attic space roof vent did not improve the overall sound transmission properties of the roof/ceiling assembly.

Further Reading - For the engineer interested in further reading, a number of other general studies have been conducted on the effectiveness of retrofit measures taken to control the transmission of aircraft noise into residential units. Following are abstracts of five reports that are recommended for additional study.

BBN - Under the Technical Studies Program of HUD/FHA, Bolt, Beranek and Newman undertook a study of insulating houses from aircraft noise. The guide, published in November 1966,* outlines a detailed procedure to be followed in determining the necessary steps to improve the noise isolation of houses subject to aircraft generated noise. Tables are provided for estimating the noise levels from various types of aircraft under conditions of runup, takeoff and landing, with corrections for distance and direction. Three levels of noise isolation improvement are described: 5-10 perceived noise level in decibels or PNdB, 10-15 PNdB, and 15-20 PNdB.

The BBN guide suggests that windows are the weakest part of the exterior surface in most houses. Windows are therefore the place to start a noise control program, first by closing the window, second by improving the acoustic performance of the window. Since windows also provide ventilation and summer cooling, keeping windows closed usually implies installing an air conditioning system if one is not already present. While the estimated cost data in the BBN guide are obsolete, the construction details provided on noise control improvements are still very pertinent.

Weissenburger - In a study** *sponsored* by the St. Louis Airport Authority, J. T. Weissenburger, et al, investigated the economic feasibility of retrofitting houses to improve their acoustical performance. The demonstration consisted of six houses located near the Lambert St. Louis International Airport. A variety of acoustical control measures were installed as remedial measures for houses impacted by airport and aircraft noise. Major attention was devoted to improving primary weak areas - windows and doors. Other area improved were exterior openings such as

---

* "Design Guide - Methods for Improving the Noise Insulation of Houses with Respect to Aircraft Noise", Report 1390 by Bolt, Beranek and Newman. Inc., Los Angeles, California, November 1966, GPO - HH1.31:19.

** J. T. Weissenberger, J. C. McBryan and L. F. Heitkamp, "Airport Related Residential Insulation Demonstration Project", Rpt. 1720, by Eng. Dynamics International, St. Louis, Missouri, June 1981, NTIS - PB 82-100777.

dryer vents, exhaust fans, and mailbox slots. Two houses were air conditioned; in two, the ceilings were improved; in one an independent wall was added. Retrofit costs (1981) ranged from $7,500 to $14,000, and averaged about $10,000. Exterior and interior noise levels were measured before and after retrofits were installed.

Weissenburger found that noise generated by an aircraft during takeoff was high in low frequency acoustic energy. On the other hand, high frequency energy was dominant during landing operations. Since low frequencies tend to interact more readily with the basic building structure, they were much more difficult to control. The standard improvements made to windows and doors were more effective against high frequency energy than against low frequencies. Replacing poor quality (in terms of air leakage) windows with high quality double glazed units was effective. When the original window unit was single glazed and of good quality with a well fitted storm window spaced from it, the replacement was counter productive. The average effective noise reduction (ENR) after retrofit was about 30 dB. It was concluded that the measures taken were not sufficient to reduce interior noise from takeoffs to acceptable levels; more extensive modifications to the walls and roofs would be required.

Wyle - NBS sponsored a critical review of the status in sound transmission through building structures, which also identified specific areas for further research.* B. H. Sharp, et al, of Wyle Research, Arlington, Virginia, conducted the investigation for NBS. They recognized three major noise transmission paths in the building envelope: (a) air infiltration (gaps, cracks and vents), (b) small wall elements (windows and doors), and (c) main panel elements (walls and roof). The synergism between acoustical control and energy conservaton was pointed out, especially as related to air infiltration reduction; also cases where the synergism did not follow. Sealing of leaks

---

* B. H. Sharp. P. K. Kasper and M. L. Montroll, "Sound Transmission Through Building Structures - Review and Recommendations for Research", Report WR 80-20, by Wyle Research, Arlington, Virginia, July 1980, NBS - NBSIR 80-250, NTIS - PB 81 187072.

to reduce air infiltration was felt to be the most cost effective measure for improving the acoustical performance, and should be performed first. When additional sound control was required, improvement of small wall elements and main panel elements should be undertaken in that order. An extensive bibliography of related references is included in the report.

Wyle - The Los Angeles Department of Airports contracted with Wyle Laboratories, El Sequndo, California, for a series of investigations for control of noise in houses adjacent to the Los Angeles International Airport. The final report covering a soundproofing pilot project was issued in 1970.* Twenty inhabited houses were involved in the project. Three stages of modification were studied: (1) minimum amount of added noise isolation, (2) intermediate amount, and (3) maximum amount. Stage 1 houses were modified to provide the owners with the option of living with doors and windows closed. Stage 2 houses required major modification of exterior doors and windows and beamed ceilings. Stage 3 houses required complete modification, including also roof/ceiling systems, floors and walls.

Stage 2 and 3 modifications generally produced results satisfactory to the homeowner, whereas Stage 1 did not. The degree of satisfaction achieved appeared to be more related to the amount of change rather than the absolute interior noise level after modification.

Wyle - In a companion report, "Guide to the Soundproofing of Existing Homes Against Exterior Noise",** also issued in 1970, Wyle Laboratories describe details of construction that will provide Stage 1, 2 and 3 degrees of increased "soundproofing".

The Wyle guide also contains a section on the "Elements of Noise Control". This section covers the fundamentals, and emphasizes the importance of controlling the noise transmission through the acoustically weakest parts of the structure as the initial concern.

* "Home Soundproofing Pilot Project for the Los Angeles Department of Airports", Report WCR 70-1 by Wyle Laboratories, El Sequndo, California. March 1970.

** "Guide to the Soundproofing of Existing Homes Against Noise", Report WCR 70-2 by Wyle Laboratories, El Sequndo, California, March 1970.

END

FILMED

9-83

DTIC